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Optimising air cooling for drive enclosures

Master's Thesis

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Abstract

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Electrical drives have continuously developed into more compact and powerful systems. Competition in this business is high, and to stay in the business it is important to keep product costs low without decreasing the quality. Cost cuts are achieved, when products are optimised by changing their design into a more adequate form. This thesis focused in optimising the air cooling of ACS880 inverters from frame sizes R1i to R4i inside Rittal cabinets, by comparing three different outlet types. The comparison was done on FloeEFD simulation software.

ABB offers kits for system integrator customers, who prefer to build the drive systems themselves. These customers have been instructed to order a roof fan outlet from ABB to ensure sufficient air cooling inside a Rittal cabinet, when using inverter modules from frame sizes R1i to R4i. The first goal of this thesis was to find out, whether the airflow would be sufficient in terms of air cooling if the fan was removed from the outlet. The airflow through the cabinet would then be generated by the fans inside the inverter modules. Second goal was to find out, if an elevated roof outlet from Rittal would be more efficient for air cooling than the outlet from ABB with fan removed.

All the inverter modules were tested inside a wind tunnel to collect pressure drop and air volume flow data. The test results were then used to find out the modules which would most likely overheat and these modules were chosen for further simulations. The simulation models were simplified by removing unnecessary features of the CAD models which would not have an effect on the final results.

The simulation results stated that when maximum amount of R4i modules are installed in a 600 mm wide Rittal cabinet without a roof fan, the ambient temperature of the cabinet will rise too high for the modules to operate reliably. Therefore, the roof fan remains the most secure and efficient solution as an outlet. However, the elevated roof outlet proved to be more efficient than the ABB outlet when the fan was removed. The elevated outlet could bring some benefits in the future due to its simple and space effective design, but to be able to use it, some further investigation and designing should be done.

Keywords Power electronics, inverter, air cooling, outlet, fan, convection, Rittal TS8 cabinet

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Taajuusmuuttajat ovat ajan saatossa kehittyneet yhä kompaktimmiksi ja tehokkaammiksi, mutta samalla myös kilpailu alalla on koventunut. Jotta tuotteet saadaan myytyä voitolla, täytyy tuotantokustannuksien pysyä alhaalla laadusta tinkimättä. Tuotantokustannuksia voidaan karsia optimoimalla tuotteita enemmän laatua vastaavaan muotoon. Tässä työssä pyrittiin optimoimaan ACS880 R1i – R4i -invertterikaappien ilmajäähdytystä, vertaamalla kolmea eri ilmanpoistorakennetta. Vertailut suoritettiin FloEFD-simulointiohjelmalla. Tutkimuksissa käytettiin Rittalin TS8-kaappimallia.

ABB tarjoaa järjestelmäintegroija-asiakkailleen kittejä, joista taajuusmuuttaja on mahdollista koota itse. Näitä asiakkaita on R1i – R4i moduulien tilauksen yhteydessä ohjeistettu hankkimaan myös kattopuhallinkitti, jonka avulla varmistuu, etteivät kaappi ja sen komponentit pääse ylikuumenemaan. Tutkimuksen ensimmäinen tavoite oli selvittää, onko R1i – R4i -invertterejä mahdollista käyttää ilman kattopuhallinta säilyttämällä sama toimintavarmuus. Näin ollen ilmanvirta kaapin läpi olisi kokonaan tuotettu moduulien sisällä olevilla puhaltimilla. Toinen tavoite oli selvittää toimiiko Rittalin tarjoama korotettu kattorakenne paremmin ABB:n kattorakenteeseen verrattuna, kun puhallinta ei ole käytössä.

Kaikki moduulit testattiin tuulitunnelissa, jossa kerättiin tietoa moduulien painehäviöistä ja ilmavirran tuotosta. Näiden testien perusteella valittiin todennäköisimmin ylikuumentumisriskin aiheuttavat moduulit simulointeja varten. Simulointimalleja yksinkertaistettiin poistamalla käytetyistä CAD-malleista ominaisuuksia, joilla ei ole simulointituloksien kannalta merkitystä.

Lopullisten tulosten perusteella R4i-moduulit tuottivat liikaa lämpöä Rittalin 600 mm leveässä kaapissa ilman kattopuhallinta toimiakseen luotettavasti. Näin ollen kattopuhallinratkaisu säilyy suositeltuna ilmanpoistoratkaisuna johtuen sen tehokkaista jäähdytysominaisuuksista. Rittalin tarjoama korotettu kattorakenne paljastui kuitenkin tehokkaammaksi kuin ABB:n kattorakenne ilman puhallinta. Korotettu katto voi myöhemmin vielä tuoda etua sen kompaktin ja yksinkertaisen rakenteen vuoksi, mutta jotta se voitaisiin ottaa käyttöön R1i - R4i -moduuleilla, vaatii se lisätutkimuksia sekä suunnittelutyötä.

Avainsanat Tehoelektroniikka, ilmajäähdytys, invertteri, ilmanpoistorakenne, puhallin, konvektio, Rittal TS8 kaappi

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Special thanks I wish for all my family and friends, who have been supporting me on my university studies. I am glad that I chose to follow my father's career path, and I thank him for all the help and inspiration so far.

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Leevi Lehtisalo

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Nomenclature

Latin Alphabet

Symbol	*Meaning*	*SI unit*
A	*area*	m^2
h	heat transfer coefficient	W/m^2K
I	*Current*	A
$\dot{m}$	*mass flow rate*	kg/s
p	pressure	Pa
p_0	total pressure	Pa
Q	volume flowrate	m^3/s
q	*dynamic pressure*	Pa
$\vec{q}$	*heat flux*	W/m^2
T	*temperature*	K
t	*time*	s
U	*Voltage*	V
V	*Volume*	m^3
v	*velocity*	m/s
P	*Heat loss*	W
x	*position along conductive material*	m

Greek Alphabet

ε	emissivity coefficient	-
σ	Stefan-Boltzmann Constant	$W/(m^2K^4)$
ρ	*density*	kg/m^3
Δp	*pressure drop*	Pa

Subscripts and abbreviations

ABB	Asea Brown Boveri
AC	Alternating Current
CAD	Computer Aided Design
DC	Direct Current
CFD	Computational Fluid Dynamics
SP	Static Pressure
TP	Total Pressure
RPM	Revolutions Per Minute

1 Introduction

1.1 Backgrounds of the study

Optimisation of products has become increasingly more important in technological companies. Competition is high and every customer is important to stay in the business. By optimisation, manufacturing costs can be reduced as the product is modified into a smarter and cheaper design. Electrical drives have developed more efficient and more compact, but as all compact power electronics, they require cooling to avoid overheating of critical components.

Cooling of electronics can be done in several ways. Traditionally air cooling has been most common cooling solution, but nowadays liquid cooling has become a very good option. Air cooling is usually cheaper compared to liquid cooling, and it does not require pump units or hoses to run the liquid. However, liquid cooled products can work in harsh environments, since they are not dependent on air quality of the installation space.

Air cooling is based on maximising the cooled surface area and increasing flow over this surface. With some electronics, it is possible to cool the product with natural convection without forcing the air to move with fans. However, with power electronics such as variable-frequency drives that are installed into compact cabinets, using forced convection in some form is almost always needed to ensure proper cooling.

Natural convection is usually the most optimal way for cooling a product. Without fans, the overall manufacturing cost decreases and there is no longer need for maintenance of the fans. Even though this may not be a possible solution for high power drives, the needed amount of fans should still be optimised to the minimum.

1.2 Objectives

This study focuses on air cooling of ABB ACS880-104 drives in Rittal cabinet. Rittal is a major distributor of power electronics enclosures, and ABB provides kits designed for Rittal cabinet for customers who prefer to assemble the drive themselves.

For ABB's customers, it has been instructed that with small frame size inverter modules from R1i to R4i, a roof fan should be installed to ensure sufficient airflow through the cabinet. Even though the roof fan has been a working solution to secure proper ventilation, the idea of a cabinet without a roof fan circulating the air only with inverter module fans has not yet been properly studied.

The first objective is to study if the R1i to R4i inverters can be used without roof fan on top of a 600 mm wide Rittal cabinet. ABB also offers kits for 400 and 800 mm wide cabinets, but the 600 mm enclosure fits the most inverter modules in comparison to its volume, which makes it the critical size in terms of overheating. Therefore, if test results are positive for the 600 mm cabinet, the result can be assumed as positive for the other cabinet sizes as well.

The second objective is to find out if the cabinet cools down better with an elevated roof structure instead of the standard ABB outlet without a fan. In this solution, the roof is simply elevated with 4 support bars, to allow the air exit easier from the cabinet.

Another objective is to collect pressure drop data of each of the studied inverter module. The data is collected by tests, which are performed using a wind tunnel. With this information combined with the heat losses from the product manual, the internal parts of the simulation inverters can be left out as they are replaced with a simulation block that holds all the correct information. As the thesis focuses on optimising the simulation cabinet, it is not important to know what happens inside the inverter modules, as long as the airflow and temperatures produced by the inverters are realistic.

To solve these questions related to cabinet airflow, a simulation software "FloEFD" will be used. Simulation models are created for a cabinet with a roof fan, without a roof fan and in the final case with the elevated roof design. When the simulation are complete, these three options are then finally compared. The simulation environment will be set to a steady 40 C° temperature, which is the highest allowed temperature for the inverter cabinet's installation space. In addition to simplification of the inverter module simulation models, also other parts in the cabinet will be simplified as well when possible to reduce the calculation time. Several features such as small holes, chamfers or screws do not make a significant change to the thermal simulation results, but they do increase the calculation phase heavily.

2 Backgrounds to drive technology

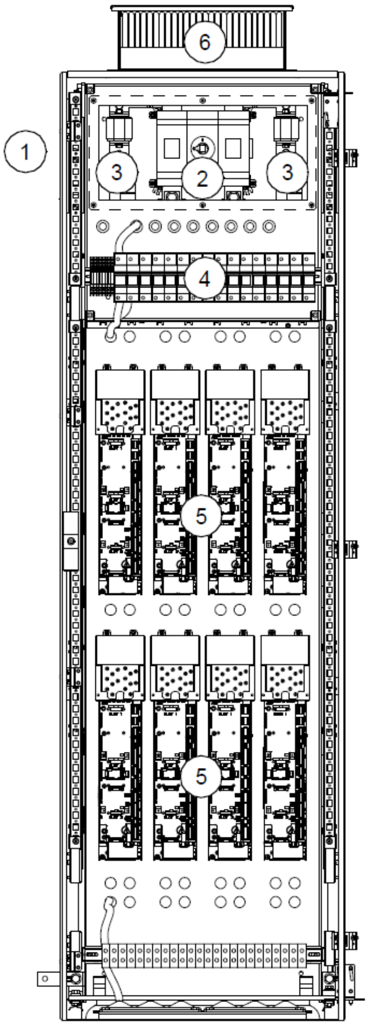
2.1 Frequency converters in general

Drive systems are commonly used to control the speed and torque of AC motors, which power anything from pumps to conveyers. This allows energy savings, since the controlled equipment can be run at optimal speed. The speed control offers smooth use with the motors as gears are no longer needed. Drives also enable a soft start for the motor with full torque, which is important for heavy machinery such as ski lifts that require steady operating. (ABB industrial drives, 2015)

A frequency converter changes alternating current (AC) to selected frequency. Drive system requires a supply unit that changes the AC supply current into direct current (DC). This direct current is then changed back into alternating current with the desired frequency by using an inverter unit. (ABB industrial drives, 2015) The size of a frequency converter depends on its power. Small converters can be 10cm wide and 20cm high, whereas bigger converters can easily be 1.5 m tall and weight over hundred kilograms.

2.2 Inverter cabinet layout and components

The inverter unit works between a supply unit and an AC motor, by converting direct current into alternating current. In the ACS880-104 units which are studied in this thesis, the inverter units are installed in a cabinet that requires multiple components to operate as seen on figure 1. The inverter cubicle has DC busbars on top of the cabinet, where the direct current flows through the DC switch and main DC fuses to the next DC fuses for each inverter unit. At the inverter unit the current is alternated to chosen alternating current and then supplied to the AC motor.



Description
Cubicle including: 1. DC input 2. DC switch/disconnector for all inverter modules 3. Main DC fuses 4. DC fuse disconnectors for each inverter module 5. Inverter modules 6. Air outlet with exhaust fan

Figure 1, Inverter cabinet layout (ABB industrial drives, 2015)

As the inverter cabinet is packed tightly with components, a roof fan is recommended for the R1i-R4i inverters which do not produce high amounts of airflow with the module fans by themselves. However, the need of the roof fan will be reconsidered in this thesis by simulating a slightly different roof design that might have a positive effect for the cooling. The Rittal cabinets used for these inverters three different width options, which are 400, 600 and 800 mm. In the 400 mm wide enclosure it is possible to fit either four R1i or R2i modules, or two R3i or R4i inverters. In the 600 mm cabinet seen in figure 1, the amount of modules is doubled, allowing to fit eight R1i or R2i, or four R3i or R4i modules. The widest 800 mm enclosure fits 12 R1i or R2i modules, or six R3i or R4i modules. The advantage of having as many inverter modules in the same cabinet as possible is that when the cabinet is combined to the row of inverters and supply units, the needed space for the whole drive system decreases.

3 Theory of air cooling

3.1 Heat transfer

Heat refers to energy that spontaneously passes through systems and it is involved with every system that has a work input (Gordon, 2000). Heat transfer is energy in motion, which can occur through a mass by conduction, from a solid to a moving liquid by convection or from body to another body through space by radiation. Air cooling is mainly based on convection, but radiation and conduction are also important factors when doing thermal design for products. (Haines, 2010)

Heat always transfers from warmer to colder, due to second law of thermodynamics. To change this, additional work to the system has to be applied. On a horizontal plane the differences in temperature, pressure and density will even out as time goes by. However, due to gravity, heated air will always travel upwards since heating expands the air making its density smaller than the surrounding air. (Haines, 2010)

Knowing how heat transfer laws work helps to design optimal thermal properties for a product. By utilizing mechanisms such as natural convection it is possible to reduce the amount of needed fans, making an air cooled product cheaper and easier to maintain. However, natural convection by itself is not often effective enough for cooling power electronics, as it cannot offer the same range of heat transfer as forced convection. (Simons, 2001)

3.1.1 Conduction

Thermal conduction refers to direct energy transfer between particles at the atomic level where heat is transferred when atoms and molecules collide. Dense materials have more atoms, creating more collisions and therefore more heat transfer. Fluids and especially gasses are less conductive, since there are less atoms to collide. (Lienhard, 2011)

From thermal design point of view, materials with high conductivity can be used to transfer heat from critical areas. Heatsinks are made of highly conductive materials such as metal alloys to move the excess heat from vulnerable components into a cooled zone. Materials with low conductivity can be used as isolation, since heat will not pass through them easily. (Haines, 2010)

Joseph Fourier introduced the Fourier's law in the early 19th century, where the heat flux, q (W/m^2) is presented as:

$$q = -k\frac{dT}{dx} \tag{1}$$

Where:

k = thermal conductivity (W/(m·K))
T = temperature (K)
x = position along conductive material (m)

Heat flux is a vector quantity, and therefore equation (1) shows that regardless if the temperature is decreasing or increasing, the heat flow will always go from higher towards lower temperatures. (Lienhard, 2011)

Thermal conductivity, k, varies for different materials, and it is dependent on the temperature. With gasses k usually increases as temperature raises while with metals it works the other way around. Both material groups have their own exceptions, and when k is needed for calculations, it is good to check if it acts approximately as a constant in studied range. (Haines, 2010) An example of different thermal conductivities can be seen in figure 2.

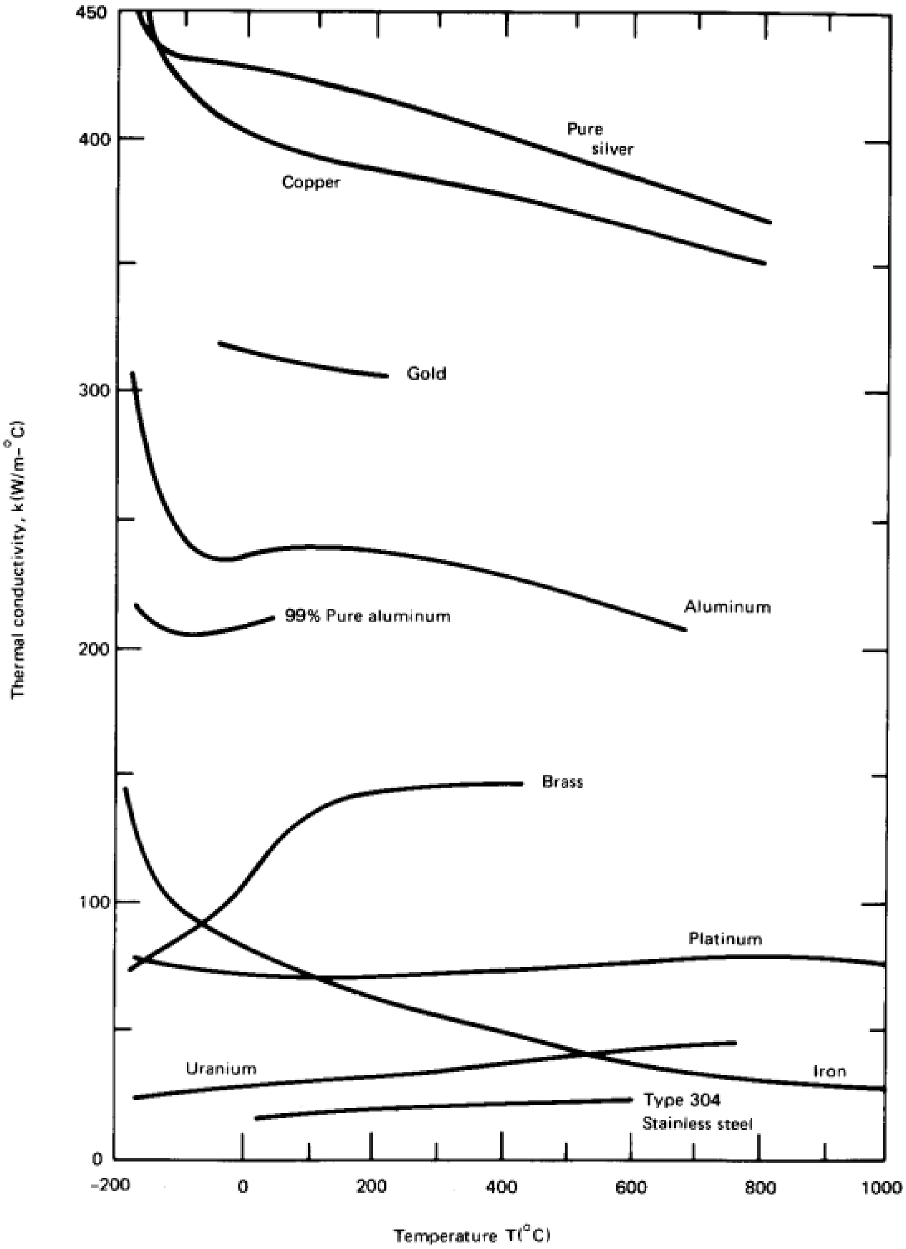


Figure 2, *Thermal conductivity for different metals (Lienhard, 2011)*

Conduction plays a major role in the heat transfer of drive enclosure cabinets. The cabinets and components inside it are mostly made out of different metals, such as the copper busbars, that have a high thermal conductivity. Also the inverter modules have heat sinks that collect excess heat from the components inside such as semiconductors.

3.1.2 Convection

Heat convection is a process where heat is carried away by a moving fluid. In a typical convective cooling situation a cool gas flows past a warm body, as in figure 3. When the cold fluid flows past the warm body, a thin slowed down region is formed in between, which sweeps along the body surface until it is mixed back into the stream. This region is called a boundary layer, and in this area heat is conducted into the moving fluid. (Lienhard, 2011)

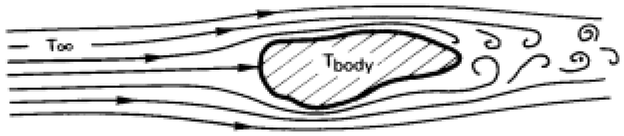


Figure 3*, Convective cooling of a heated body (Lienhard, 2011)*

In a state where the body temperature remains constant the convective cooling equation is following:

$$q = \bar{h}\left(T_{body} - T_{\infty}\right) \tag{2}$$

This is known as the steady state form of Newton's law of cooling, where T_{∞} is the temperature of oncoming fluid, T_{body} is temperature of the warm body and constant *h* is film coefficient or heat transfer coefficient. The bar over *h* indicates that the film coefficient is averaged value over the surface body. The unit for *h* is W/m^2K. (Lienhard, 2011)

In reality Newton's formula for convection is not very accurate, since $\bar{h}$ depends on the temperature difference (ΔT) between the body and the fluid. The heat transfer coefficient also varies between forced and free convection, and it is also effected by surface roughness or geometry. (Haines, 2010)

Convection can be divided into natural and forced convection. Natural convection is driven without external work. For example, all electrical components have a certain amount of power loss, causing the air around them to heat up. As the air heats up, it expands and receives a lower density than the surrounding air making it lighter and move upwards. This generates a loop, where new cool air with higher density replaces the heated up air that naturally cools the component. (Haines, 2010)

In forced convection the airflow is created with an external device such as a fan or a pump. Forced convection is needed in a vast amount of commercial devices such as computers, refrigerators or car engines. In many cases both forced and natural convection occur at the same time, so it is important to consider them as an entity. (Haines, 2010)

Frequency converter cabinets are divided into air and liquid cooled, that both use forced and natural convection for cooling purposes. This thesis focuses on the air cooled cabinets, where the airflow is created with fans. The fans are normally located inside the inverter modules, and in some cases also at the top of the cabinet to ensure sufficient airflow. Natural convection also plays a part, since the air inlet is located at the bottom of the cabinet, and the outlet at the top. This ensures that heated air can exit naturally as it raises up, while cool air enters the cabinet from below.

3.1.3 Radiation

Heat transfer by thermal radiation is occurring constantly everywhere by process of electromagnetic radiation. All bodies emit energy flux depending on the temperature of the body and its surface properties. In many cases radiant heat from cooler bodies can be neglected in comparison to conduction and convection. However, there are situations such as conduction and convection being suppressed by insulation where radiation makes a significant amount of heat transfer in the studied system. (Lienhard, 2011)

The full electromagnetic spectrum includes numerous range of wavelengths, of which thermal radiation is a small part. Table 1 shows the scale of thermal radiation in comparison to all other wavelengths.

Table 1, Forms of the electromagnetic wave spectrum (Lienhard, 2011)

Characterization	*Wavelength, λ*	
Cosmic rays	< 0.3 pm	
Gamma rays	0.3–100 pm	
X rays	0.01–30 nm	
Ultraviolet light	3–400 nm	***Thermal Radiation 0.1–1000 μm***
Visible light	0.4–0.7 μm	
Near infrared radiation	0.7–30 μm	
Far infrared radiation	30–1000 μm	
Millimeter waves	1–10 mm	
Microwaves	10–300 mm	
Shortwave radio & TV	300 mm–100 m	
Longwave radio	100 m–30 km	

Heat transfer from an object to its surroundings by radiation can be calculated with Stefan-Boltzmann Law:

$$q'' = \varepsilon\sigma\left(T_1^{\,4} - T_2^{\,4}\right) \tag{3}$$

Where:

q = heat transfer per unit time (W)

ε = emissivity coefficient

σ = 5.6703×10^{-8} $(W/(m^2K^4)$ - The Stefan-Boltzmann Constant

T_1 = temperature of emitting object (K)

T_2 = temperature of surroundings (K)

Due to the fact that both the temperatures in the equation are raised to the fourth power, the temperature difference does not significantly affect the amount of heat transfer and with low temperatures the heat transfer is light. However, the temperature difference is needed for radiative heat transfer, because without it all the surfaces are emitting and receiving thermal energy at the same rate. (Lienhard, 2011)

The drive cabinets include heated components such as busbars and fuses that can heat up to 120 °C. Assuming the cabinet would be in normal 20 °C room temperature with maximum emissivity (ε = 1), the heat transfer by Stefan-Boltzmann law would be following:

$$q'' = 1 \cdot 5{,}6 * 10^{-8} \left[(120 + 273)^4 - (20 + 273)^4 \right] \approx 925 \left[\frac{W}{m^2} \right] \quad (4)$$

In normal situation, the temperatures of the components stay around 80 °C, and air inside the cabinet is approximately 40 °C. With these temperatures, the heat transfer rate is:

$$q'' = 1 \cdot 5{,}6 * 10^{-8} \left[(80 + 273)^4 - (40 + 273)^4 \right] \approx 330 \left[\frac{W}{m^2} \right] \quad (5)$$

In reality, the emissivity coefficient is lower than 1, which would make the heat transfer rate by radiation even smaller. The components with high temperatures do not have very large surface areas, which also reduces the amount of transferred heat.

3.2 Fluid dynamics

Fluid Mechanics is a fundamental area of physics that deals with behaviour of fluids both in rest and in motion. It considers fluid properties such as density and viscosity, and relates to other aspects of physics such as thermodynamics and heat transfer.

3.2.1 Finite control volume analysis

Practical problems related to fluid dynamics usually require analysis of the behaviour of the contents of a finite region in space, also known as the finite control volume analysis. This analysis can be applied to a wide range of problems, and with air cooled products it can be used to solve airflow rates at different shaped objects, such as drive cabinets studied in this thesis. Finite control volume formulas are based on fundamental principles of physics such as conservation of mass, law of motion and the laws of thermodynamics. (Young, 2012)

Mass flow rate $\dot{m}$, in a controlled section and under steady flow is:

$$\dot{m} = \rho A \mathrm{v} = \rho Q \tag{6}$$

Where ρ is the fluid density, v is a velocity component normal to area A and *Q*=v*A* is the volume flowrate (m^3/s). (Young, 2012)

When the flow in a studied system is steady, the time rate of change of mass of the control volume in the system is zero. Therefore the net amount of mass flow is also zero:

$$\sum \dot{m}_{out} - \dot{m}_{in} = 0 \tag{7}$$

In a case where a steady flow with only type of specific fluid flows through different sections, the mass flow remains constant:

$$\dot{m} = \rho_1 A_1 V_1 = \rho_2 A_2 V_2 \tag{8}$$

In steady flow situations this means that by knowing volume flow rate at one point of the system, it can be calculated for other sections with different size and shape. (Haines, 2010)

3.2.2 Field representation of fluid flow

Fluids consist of tightly packed particles, and when a fluid is moving the movement can be seen as continuum. Thus, at given instant in time, fluid properties such as velocity, acceleration or pressure can be given as a function of the fluid's location. The representation of these fluid parameters as functions in the spatial coordinates is called a field representation of the flow. Important thing to consider is that the specific field representation might differ at different times, so usually many other parameters have to be determined. (Young, 2012)

The field representation can be used on different properties of the fluid, but probably the most useful and important is the velocity field:

$$V = u(x, y, z, t)\hat{\imath} + v(x, y, z, t)\hat{\jmath} + w(x, y, z, t)\hat{k} \tag{9}$$

Where *u, v* and *w* are the components in *x,y* and *z* directions for the velocity vector. With all the 3 different dimensions, the flow is called three dimensional flow. In some cases one of the velocity components is so small compared to the others, that it can be neglected making the analysis two dimensional. (Young, 2012)

The field representation of fluid flow is useful way of viewing how the fluid travels through the studied space as seen in Figure 4. With combination of air velocity and temperature, the field helps to position a cooling fan to optimal location, guaranteeing sufficient cooling for the critical components. Calculating three dimensional velocity vectors can be done relatively fast with modern computers, and the simulation programs offer good amount of tools to predict how the cooling solution will work.

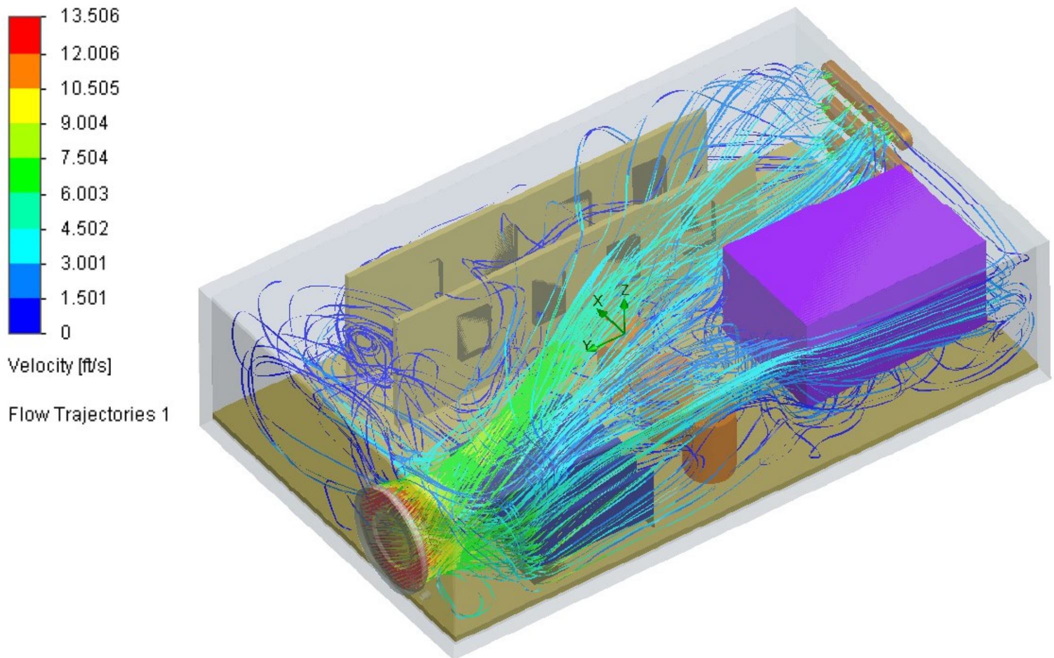


Figure 4, *Example of three dimensional fluid velocity vectors (Mentor Graphics, 2015)*

3.2.3 Pressure calculations

In design of airflow systems, there are three pressure types that often used for calculations. These are total pressure p_0, static pressure *p* and dynamic pressure q. The total pressure is the sum of static and dynamic pressures.

$$p_0 = p + q \tag{10}$$

Measuring pressure differences in airflow studies is popular due to the fact that pressure is a needed component for many flow related calculations. There are several different pressure measurement devices, such as gadgets monitoring the height of a water pillar. Changes in pressures cause changes in amount of airflow, and have an effect on fan performance. (Haines, 2010)

Pressure losses in pipe systems behave in a similar way compared to an electric circuit components. As different components such as vents and filters are installed in series, the total pressure loss is the sum of the individual pressure losses. In parallel installation the pressure drop is evenly distributed to each pipe. (Young, 2012)

Pressure losses in cabinets or duct systems occur in different ways such as friction losses or dynamic losses. Friction losses are created by friction and turbulence and depend on the fluid viscosity. For example, as air moves in a straight duct, the air molecules at the edges rub against the wall causing them to slow down. These slowed down air molecules then collide with other air molecules nearby, making the flow slower near the duct walls.

As drive cabinets are short compared to air ducts, the friction losses are relatively small. The cabinet walls are not very rough, and distance that the air travels does not create a significant pressure drop. However, what causes pressure drop is that the drive cabinets are not empty as the pipe in figure 5. The pressure drop in drive enclosures is mainly formed of dynamic losses that occur when the air flows through and by the components inside the cabinet.

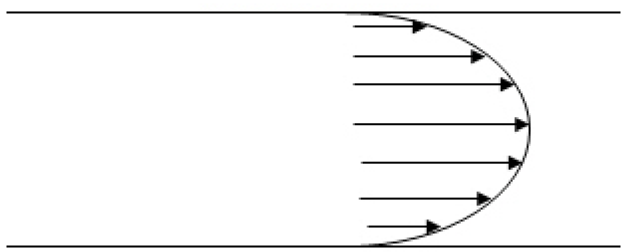


Figure 5*, Laminar flow in a pipe (Haines, 2010)*

In this thesis, pressure losses through the inverter modules will be measured to form a pressure drop curve for a simple simulation model. This enables replacing all the components inside the inverter module with a simple porous medium block that has the same pressure drop values as the tested module. With this change in the simulation design, the calculation time is reduced significantly.

To form the pressure drop curve for the modules, the difference between the static pressures before and after the module are recorded at variable volume flows. Therefore the pressure drop can be described as following:

$$\Delta p = p_2 - p_1$$

Where Δp is the pressure drop, p_2 is the static pressure of the air after the module and p_1 is the static pressure of the air before entering the module. (Wuori, 1992) More details about the test setup and methods are presented in chapter 5.

3.2.4 Computational fluid dynamics

Computational fluid dynamics (CFD) is a branch of fluid mechanics that uses numerical methods and algorithms to solve problems related to fluid flow. With mathematical predictions calculated by modern computers, CFD can give good view on fluid flow and heat transfer rates that are close to real life test results. (Young, 2012)

For solving engineering problems there are three different approaches. These are:

- an experimental approach
- a computational approach
- a computational-experimental approach

These methods all have their advantages and disadvantages. A pure experimental test will not require validation of obtained results, but is in many cases time consuming and expensive. When simulating with CFD, results can be obtained fast and relatively cheap, but assurance that the results are proper must base on numerous mathematical verifications and validations. To combine the advantages of both experimental and computational approach, these two are usually combined. (Young, 2012)

CFD replaces partial differential equations with discretized algebraic equations that approximate the partial differential equations. By numerically solving these equations, is flow field points in certain time and space obtained. Navier-Stokes equations provide solutions for infinite number of points in the fluid flow, but analytical solutions are only available for limited number of simplified flow geometries. This limitation is surpassed by discretizing these equations into algebraic form for the computer to solve. (Young, 2012)

The CFD program used for simulations in this thesis is called FloEFD. This simulation software runs on CREO, which is a CAD program that ABB uses for 3D modelling. By having the CFD and the CAD program working together there is less configuration work than having two individual programs.

4 Drive enclosure cooling

As variable frequency drives are developed, the new models usually work with higher power ratings compared to the previous models without increasing the enclosure size. This is enabled by new more efficient components and layout designs. However, as drive modules are packed more densely inside cabinets, it is important to make sure that they will not overheat.

Cooling the enclosures is done by either air or liquid cooling. Air cooled solutions are usually easier to install and require less components, but are dependent on the air quality and temperature of the installation space. Liquid cooled cabinets can operate in more demanding environments, but require for example pump units to operate which increases the drive system size and cost. As this thesis focuses on the air cooled cabinets, this chapter will go through various aspects that have to be considered when designing an air cooled enclosure.

4.1 System characteristics

Drive enclosures all have their own “system resistance” which is a term referring to static pressure. System resistance is the sum of all static pressure losses in the enclosure. Pressure drops are created by the shape of the enclosure, and by filters and equipment inside the cabinet. The system resistance varies with the square of the airflow volume through the cabinet, causing significant increase in the system resistance as the airflow grows.

The system resistance can be measured with existing systems, or simulated in the designing phase. Depending on the system resistance, it will be determined how much volume of air the fan can move.

4.2 Fan characteristics

“A fan is a device for moving air which utilizes a power driven, rotating impeller” (Haines, 2010). Fans used in electronics cooling can be categorised into two basic groups, which are centrifugal and axial. These two groups can be seen in figure 6 below.

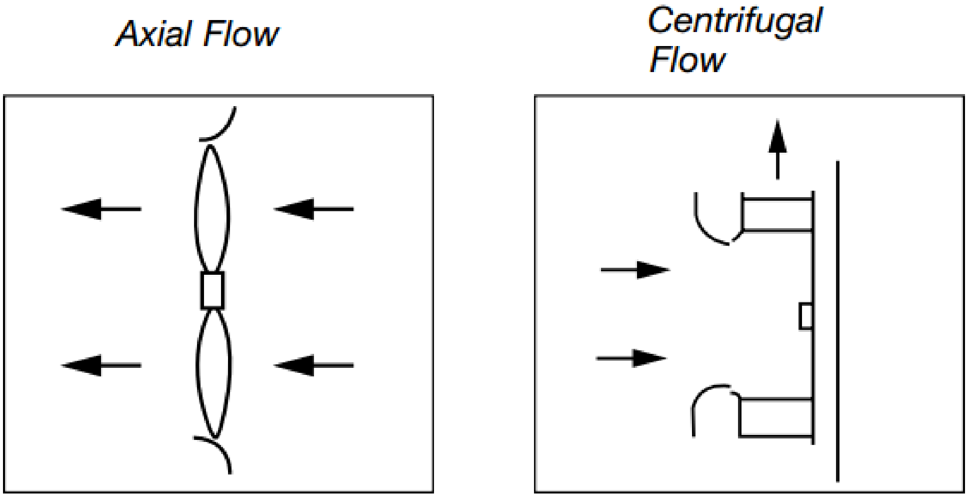


Figure 6. ***Axial versus radial fans (Aerovent, 2000)***

When air density and fan size are considered constant, following equations apply:

$$Q_2 = Q_1 \frac{RPM_2}{RPM_1} \tag{11}$$

$$SP_2 = SP_1 \left(\frac{RPM_2}{RPM_1}\right)^2 \tag{12}$$

$$TP_2 = TP_1 \left(\frac{RPM_2}{RPM_1}\right)^2 \tag{13}$$

$$P_2 = P_1 \left(\frac{RPM_2}{RPM_1}\right)^2 \tag{14}$$

Where:

Q = airflow rate, m^3/s

SP = static pressure, Pa

TP = total pressure, Pa

P = power, W

subscript$_1$ = original conditions

subscript$_2$ = new conditions

These fan laws determine that the airflow varies directly as the change in fan speed, while pressure and power vary as the square of the change in fan speed. (Haines, 2010)

When selecting a fan, it is important to choose the optimal type of fan for the use. In some cases it important that the fan will operate under high static pressure, or in other situations the volume flow needs to be as high as possible. To optimise the needed power for the fan, it important to choose the right size and properties. When the fan runs at its recommended range, it will work the most reliably, efficiently and also in most cases with less noise. (Tong, 2011)

As seen in the figure 7 below, fans can create more volume flow when there is less static pressure to work against. Some fan types are sensitive to small changes in pressure at some regions, which can make them unreliable at that work range. (Tong, 2011)

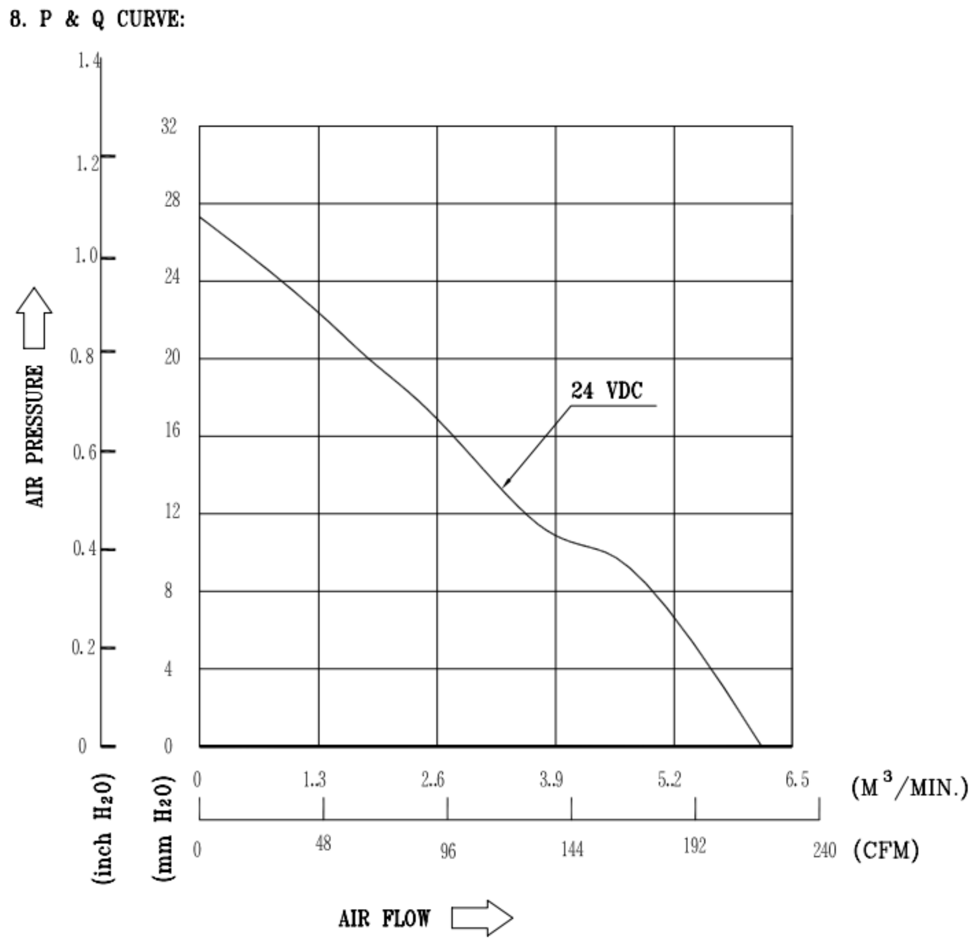


Figure 7, Example of a 24V axial fan performance curve (Delta Electronics, 2009)

4.2.1 Centrifugal fans

The cabinets studied in this thesis use centrifugal fans on top of the enclosures for forced air outlet. The air outlets are located on top of the drive cabinet and often there is not much free space between the top of the cabinet and the ceiling of the installation room. To ensure that the hot air can exit the enclosure freely, should the air exit trough the sides of the outlet. For this purpose centrifugal fan is a good choice, since it changes the direction of the incoming and outgoing air by 90 degrees as seen in figure 6, guiding the air straight to the outlets.

A centrifugal fan produces pressure and air movement by a combination of rotating tangential velocity and centrifugal radial velocity. Figure 8 demonstrates how these velocities combined form a net velocity vector. (Haines, 2010)

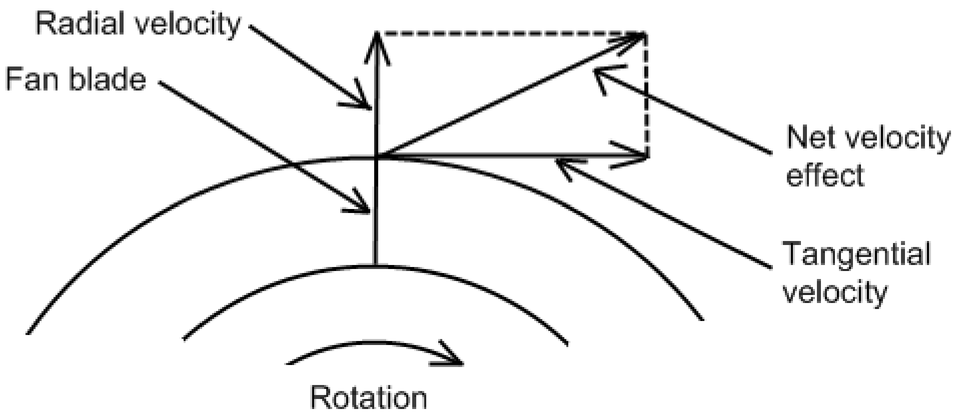


Figure 8*. Principles of centrifugal fan (Haines, 2010)*

The fan characteristics with centrifugal fan depend on the type of the blade used. Typical shapes for the fan blade are forward curved, backward curved and straight radial, which can be seen on figure 9. Also the geometry of inlet cone, fan wheel and scroll effect the fan performance. As the fan blade gets longer or narrower, can higher pressures be achieved but with reduction in flow rates. (Huhtaniemi, 2009)

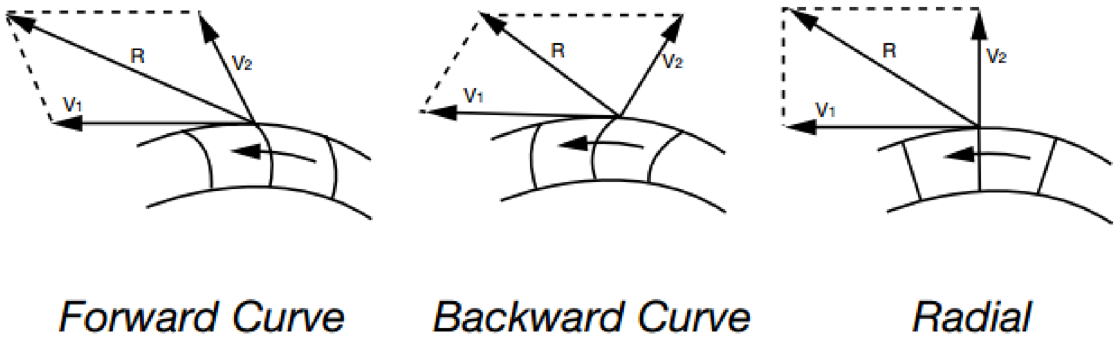


Figure 9*, Radial fan types (Aerovent, 2000)*

Advantage of forward curved fans is that they can produce relatively high airflow with less RPM than other fan blades. A disadvantage for forward curved fan blades is that they have high power requirements at or near free delivery. Backwards curved fans, which is the type of the roof fan studied in this thesis, produce airflow with higher static pressure and lower velocity. The main advantage with this blade type is the non-overloading factor, since the amount of needed power drops back down when going near the max airflow zone. (Haines, 2010)

4.2.2 Axial fans

Axial cooling fans have a simple design, where air is forced to move parallel to the central shaft around which the blades rotate. This simplistic design makes axial fans compact, which makes them a popular choice for cooling small electronics. A downside of the design is that axial fans blades are not covered, generating a notable amount of noise at high rotation speeds. (Tong, 2011) An example of axial fan used inside an R1i inverter module can be seen in figure 10.

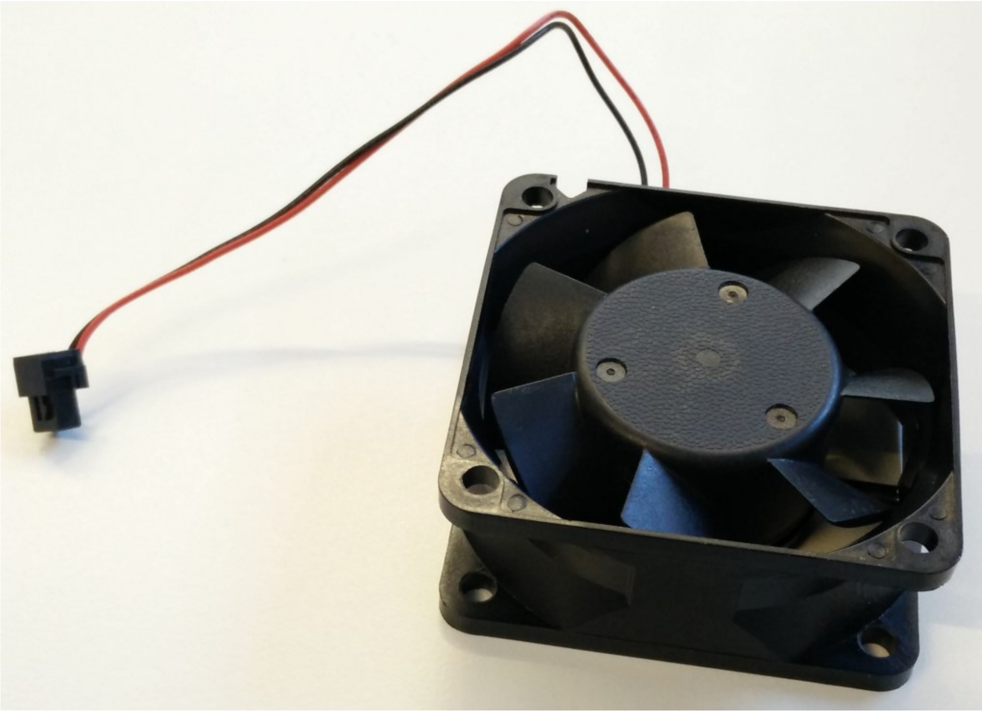


Figure 10*, 24V DC axial fan*

The performance of an axial fan is based on shape and pitch of the blades, the ratio of hub diameter to tip diameter and by the number of the blades. High hub to tip ratios (0.6-0.8) relate to lower flow rates and higher pressures than small hub-to-tip ratios (0.4-0.5). (Haines, 2010)

Unlike radial fans that push air away from the blades, axial fans blow air linear to the direction they are pointed. This makes them easy to pinpoint towards the component that requires cooling. (Haines, 2010) Due to the simple shape and size of the axial fans, they can be stacked in series or parallel to maximise air-cooling properties. When fans are installed in parallel they provide more volume flow rate, whereas installed in series, the created static pressure is increased. Therefore parallel installation should be used in cases where system resistance is low and series installation for high system resistance enclosures to ensure sufficient airflow despite high pressure losses in the system. (Tong, 2011)

4.3 Filters

A filter is a device for removing contaminants in the moving fluid. ABB cabinets have inlet and outlet filters with different IP-class options. The IP-code classifies and rates the degree of protection provided against intrusion, which can for example be a finger, dust or water. As IP class number gets higher, the amount of filtering efficiency increases.

Filters cause pressure drop, which makes them an important factor to consider in flow calculations. The pressure drop at the filter is highly related to its efficiency. The pressure drop is also increased as the filter collects more dirt. As the pressured drop increases in the cabinet, the needed amount of power for the outlet fan increases.

ABB cabinets have three main type of inlet and outlet filters, which are IP20, IP42 and IP54, as seen in figure 11. While filter holes get smaller as the IP rating grows, IP54 filters also include a coarse filter carpet to ensure proper contaminant removal.

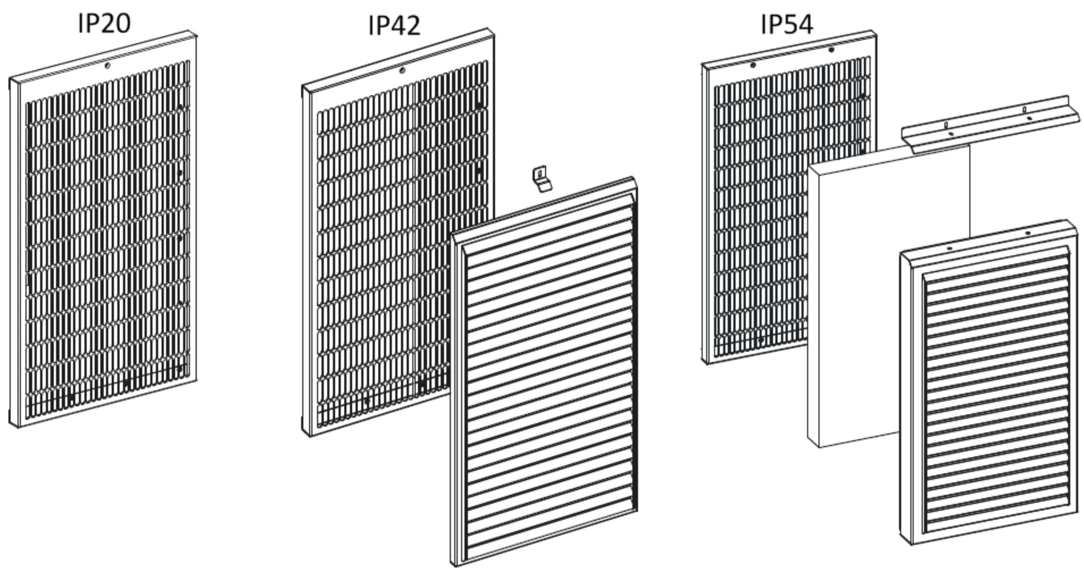


Figure 11*, Example of 400 mm wide inlet filters (ABB industrial drives, 2015)*

When studying the airflow inside the cabinet, should the highest IP class filters be used in the simulations to ensure that sufficient amount of cooling is obtained even with the highest pressure drop causing components. As the IP54 filters are designed to be used only with a roof fan, the IP42 was chosen to be used in the simulation of this thesis.

5 Pressure drop measurements

The tests presented in this thesis were done on the ABB ACS880 air cooled modules for frame sizes from R1i to R4i. The aim of these tests was to study the pressure drop of each module size to simplify the simulation models. By monitoring the static pressure before and after the tested module, it is possible to acquire the pressure drop at a certain mass flow.

5.1 Test setup and measuring equipment

Tests done regarding the thesis were executed in the ABB wind tunnel. The basic layout structure of the tunnel is demonstrated in figure 12. The tested modules are installed to the testing space, where airflow is forced to go through the modules by blocking all other routes with air blockers. This allows measuring static pressure before and after the module inside the testing space.

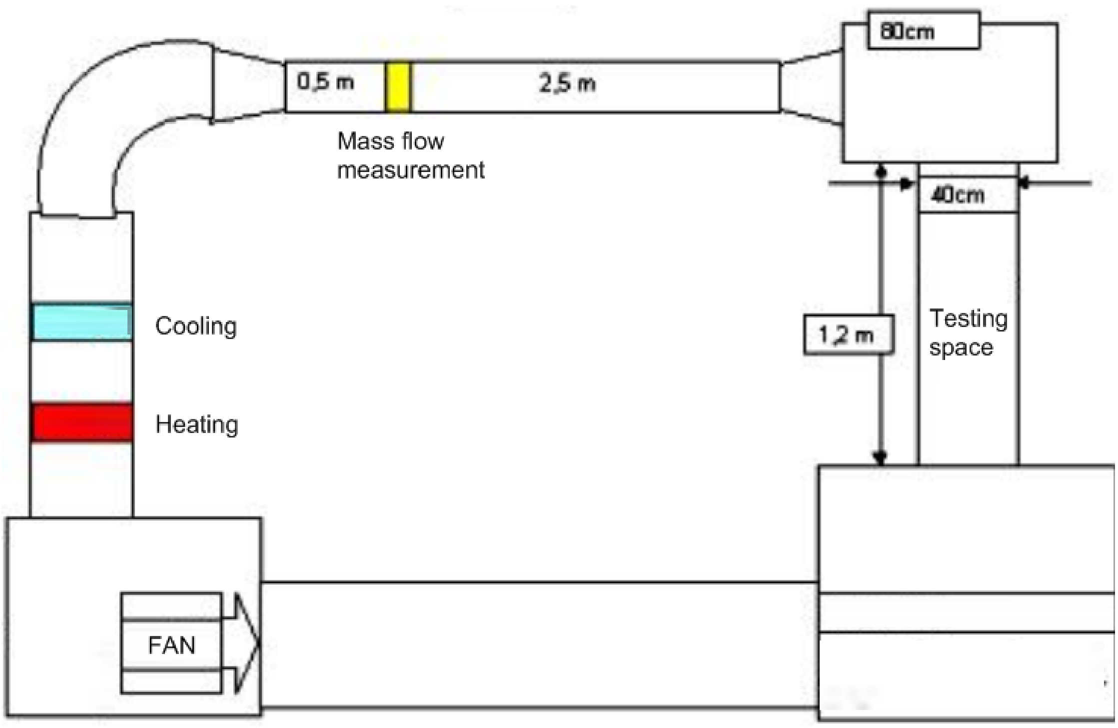


Figure 12*, Wind tunnel test-setup layout (Koivuluoma, 2000)*

To provide accurate results, the air inside the tunnel is kept at a steady temperature by water cooling and with a heater inside the tunnel. The airflow is created by ABB GTAB –1-031 centrifugal fan with backwards curved fan blades. It is powered by a 1.1 kW motor that is controlled by ABB ACS 143-4K1-3 frequency converter.

The mass flow of the air inside the wind tunnel is measured by a *Sensyflow VTS* hot-film anemometer seen in figure 13. It monitors the heat transfer of any specific type of gas, which is then used to determine flow inside the pipe where the anomometer is installed. Taking the standard density of the gases into consideration, the standard volume flow rate can be displayed without additional pressure and temperature compensation.

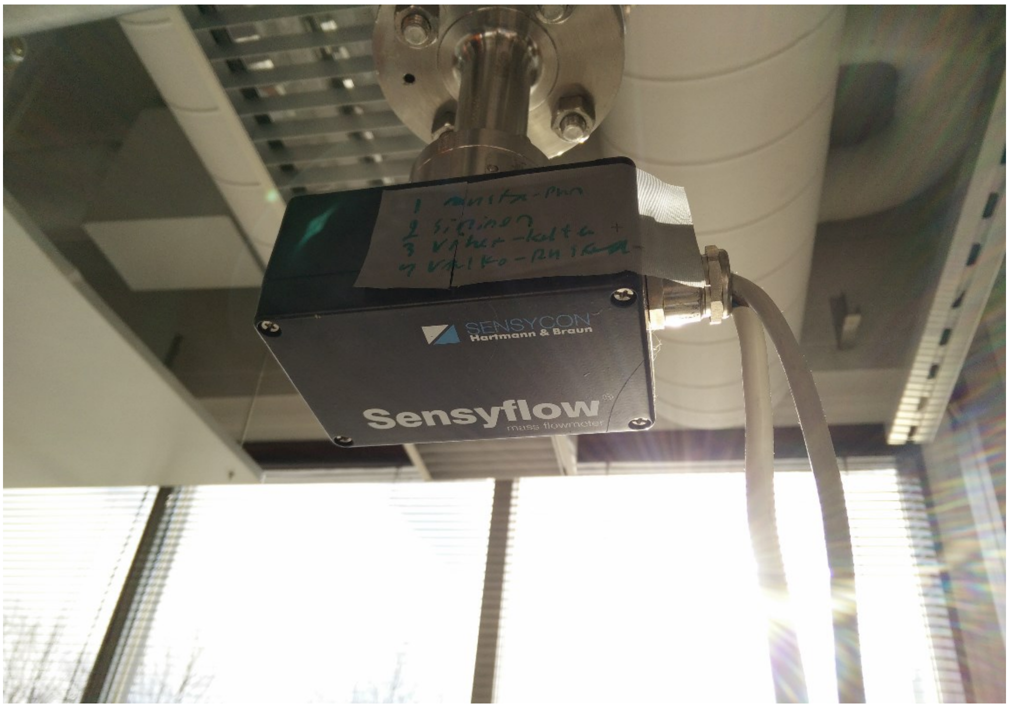


Figure 13, ***Sensyflow VTS hot-film anemometer***

The final mass flow rates are obtained by connecting the Sensyflow monitoring device with an *Agilent 34970 A* data logger presented in figure 14. The data logger is then given specific gain and off-set values, which turn the measured data into mass flow displayed real time on the data logger screen.

Figure 14, *Agilent 34970 A* data logger

To create pressure loss curves for the modules, also pressure drop values need to be obtained in addition to the mass flow. Static pressures are measured at module's inlet and outlet compartments. The pressures are monitored with a Mikor AP170S micro manometer that is connected to holes in the cabinet walls with plastic tubes. The pressure loss trough the module is obtained by simply subtracting the outlet side pressure from the inlet side pressure. The micro manometer with the tubes can be seen in figure 15.

Figure 15, ***Mikor AP170S - Micro manometer***

5.2 Test preparations

Each test started by installing measured module into the testing space. Next step was to isolate testing space into two compartments, divided at the air inlet with horizontal air blockers, as seen in figure 16. This forced all the air to move through the module, thus enabling to record the volume flow at the module.

Figure 16*, Installing module and air blockers into the testing space*

The air blockers were made for each test separately, using mainly cardboard and plenty of duct tape as material. For frame sizes R1i and R2i an additional wooden installation plate was made, since the installation space didn't have a proper place to attach the modules.

For R4i and R3i modules one unit was enough for the measurements, but with the smaller frame sizes the testing space was filled with three drives for each test. This was done because the tunnel can only give accurate mass flow ratings from 70 kg/h onwards, where the mass flow through the R1i and R2i modules is approximately 35 kg/h.

In a normal situation the module fan is powered by the module itself, so it will only work when the drive is running. However, the pressure drop tests did not require a module to be turned on, so an external power source was used to power the module fan. The used power source is shown in figure 17. The power supply enabled to run the module fans at steady 24V DC current, which was needed for all of the fan types.

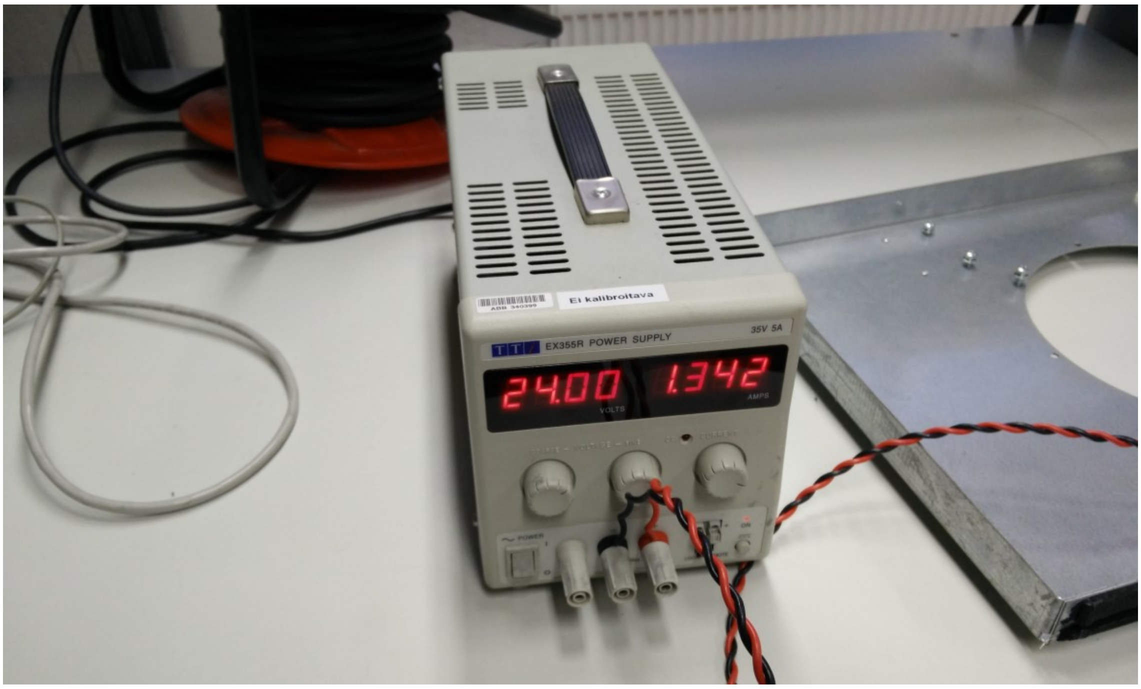


Figure 17, ***TTi EX355R Power Supply***

The airflow inside the wind tunnel was measured with the anemometer introduced in chapter 5.1. However, to be able to record these readings, the anemometer had to be connected with a data logger. This was done by using *Agilent 34901A Data Acquisition/Switch Unit,* seen in figure 18. The wires from anemometer were connected to the data acquisition unit, which was then inserted to the Agilent data logger.

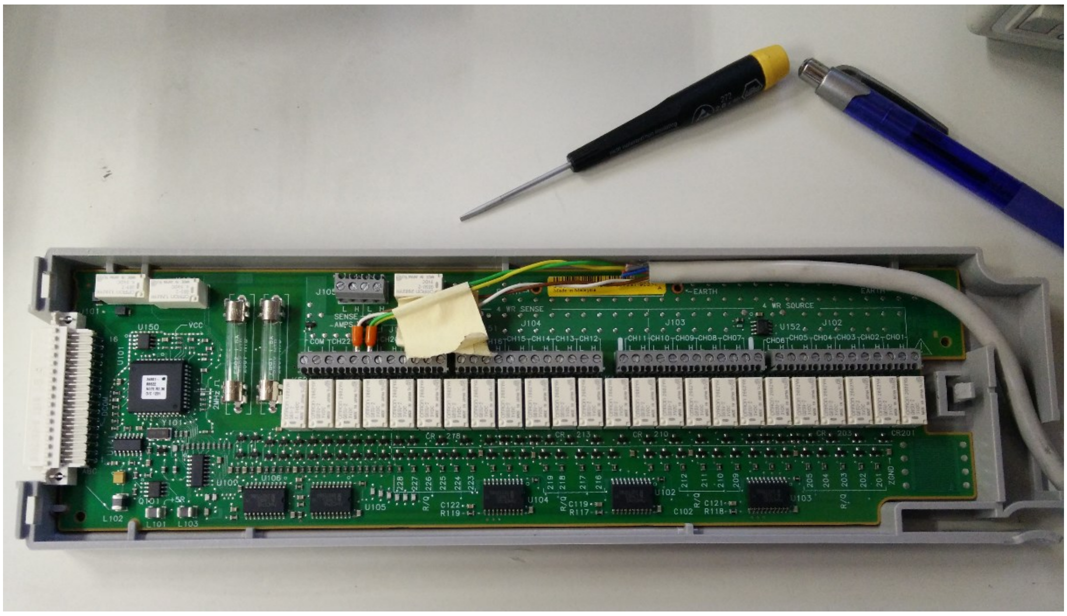


Figure 18, ***Connecting Sensyflow to the datalogger with Agilent 34901A Data Acquisition/Switch Unit***

The wind tunnel testing space had holes for pressure measurement plastic tubes on several locations. For the tests 4 holes were chosen and the others were blocked. These 4 holes were situated on the side wall and on the front door, on both lower and upper compartments of the tested module. This allowed using two micro manometers for measuring pressures simultaneously, thus ensuring that the average pressures inside the testing space were recorded both in the inlet and the outlet sides. The micro manometers were first zeroed at the room normal pressure, and then connected to the tubes.

The tests were done for each module with two different approaches. In the first test the modules were run with fan on, and in the second test the fans were off. The first test was started at the situation, where pressure loss through the module was 0, so pressures in both inlet and outlet compartments were the same. The 0 pressure point indicates how much mass flow the module can produce when there is no external flows involved. To find the state where pressures were equal, the wind tunnel fan speed was adjusted until both manometers were showing zero Pascal. Afterwards the wind tunnel fan was given higher RPM, until the pressure drop started increasing. The flow rates from the data logger and pressures from the manometers were then recorded until enough data was collected to form a pressure drop chart.

The second test with the inverter modules was done with the module fans turned off. As the module does not provide any airflow itself, the point where the pressure drop is at zero is also the point when there is no airflow through the module. As the wind tunnel could give accurate mass flow results from 70 kg/h onwards, this was the point where the tests started.

6 Cooling simulations

As mentioned before, the simulation software used in this thesis is called FloEFD. It offers good amount of tools to simulate how the air-cooling process works in the ABB drive enclosures. The simulations calculate temperatures of components, the movement of air and pressure drops through the components. Some components such as the inverter modules were simplified for the simulations by separately testing the pressure drop and applying these properties straight to FloEFD.

As the ACS880-104 is an existing product at ABB, it has complete CAD models that were used as a base for the simulation models. However, the existing CAD models include small components such as screws and small holes in the frame structure would slow down the calculation phase, but not have a significant effect on the end results. To simplify the simulation model, almost every part in the exiting CAD models were remodelled with simpler shapes, allowing fast calculation process.

To keep the amount of the simulation cabinet variations in a reasonable amount, the R2i and R3i cabinets were delimited from the simulations. The R3i inverter module produces approximately equal amount of airflow in comparison to the R4i module, but has significantly less heat losses. This allows the assumption that if the R4i cabinet runs cool enough, the R3i cabinet will do the same. The R2i cabinet was left out from the simulations, because the R2i modules are similar in size with the R1i version while providing twice as much volume flow. With the R1i invert unit providing the least volume flow, the simulations will find out if this is enough to create flow through the cabinet without an outlet fan. More information about the inverter unit volume flows can be found in the “Test results” chapter 7.1.

6.1 Simulation cabinet base

The simulation model can be separated into two basic compartments which are the base cabinet and the air outlet. The main objective of the simulations was to compare the different air outlets with the same base cabinet. For the cabinet base, two different versions were created that were R4i cabinet with four inverter units and R1i cabinet with eight modules. These simulation enclosures are demonstrated in the figure 19.

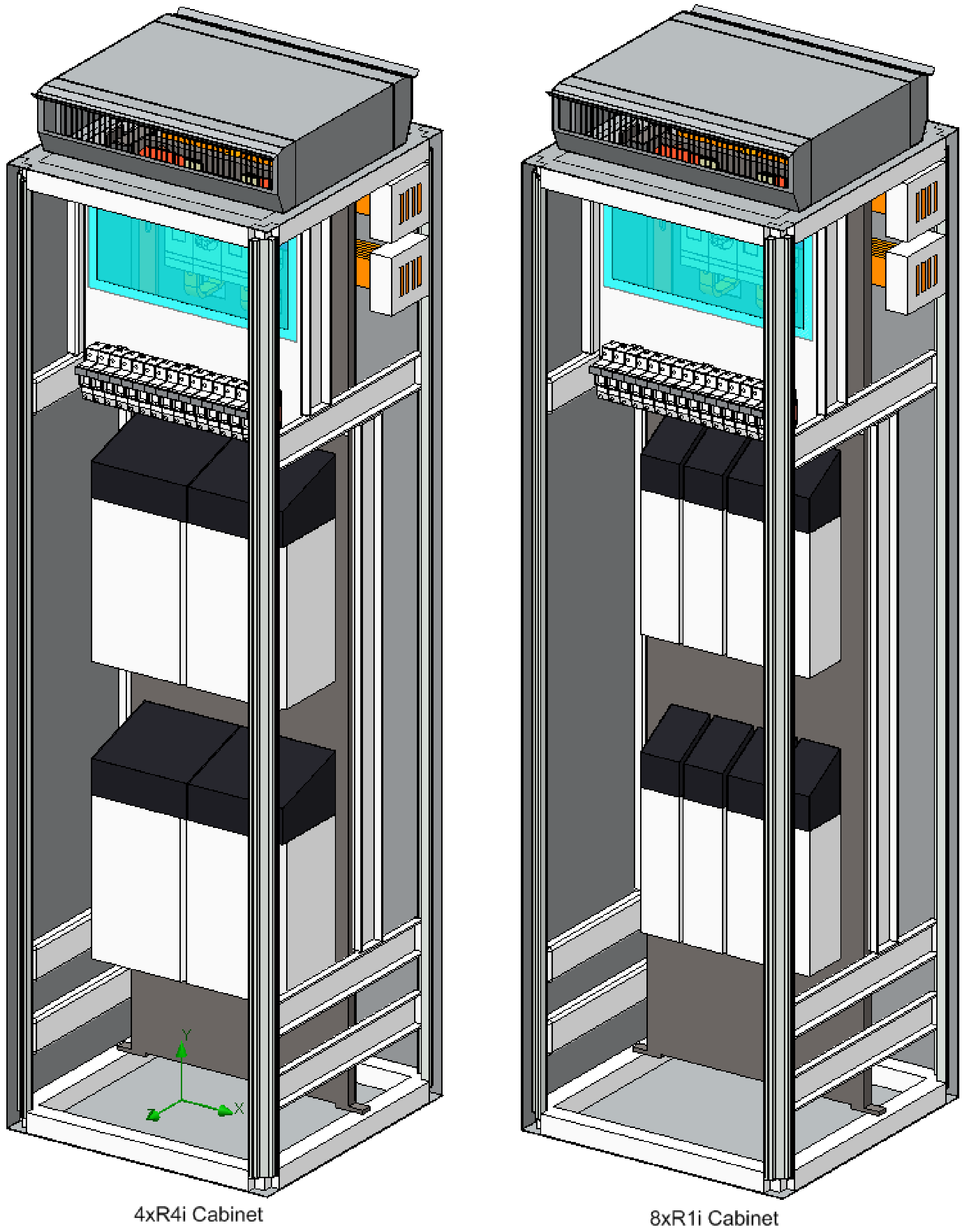


Figure 19, Simulation cabinets of 4xR4i and 8xR1i

As mentioned before, most of the cabinet components were remodelled for the simulations. When studying the air cooling properties of a drive cabinet by simulating, it is important to get accurate results on the amount of airflow created and heat produced by the components inside the studied enclosure. The components of the simulation cabinet are demonstrated in figure 20. Airflow inside the cabinet is created by the fans inside the inverter modules, and also by a roof fan in one of the outlet options. All the electrical components inside the enclosure have heat losses, and the values for these were gained from ABB test results and manufacturer datasheets, which were then input to the simulation program.

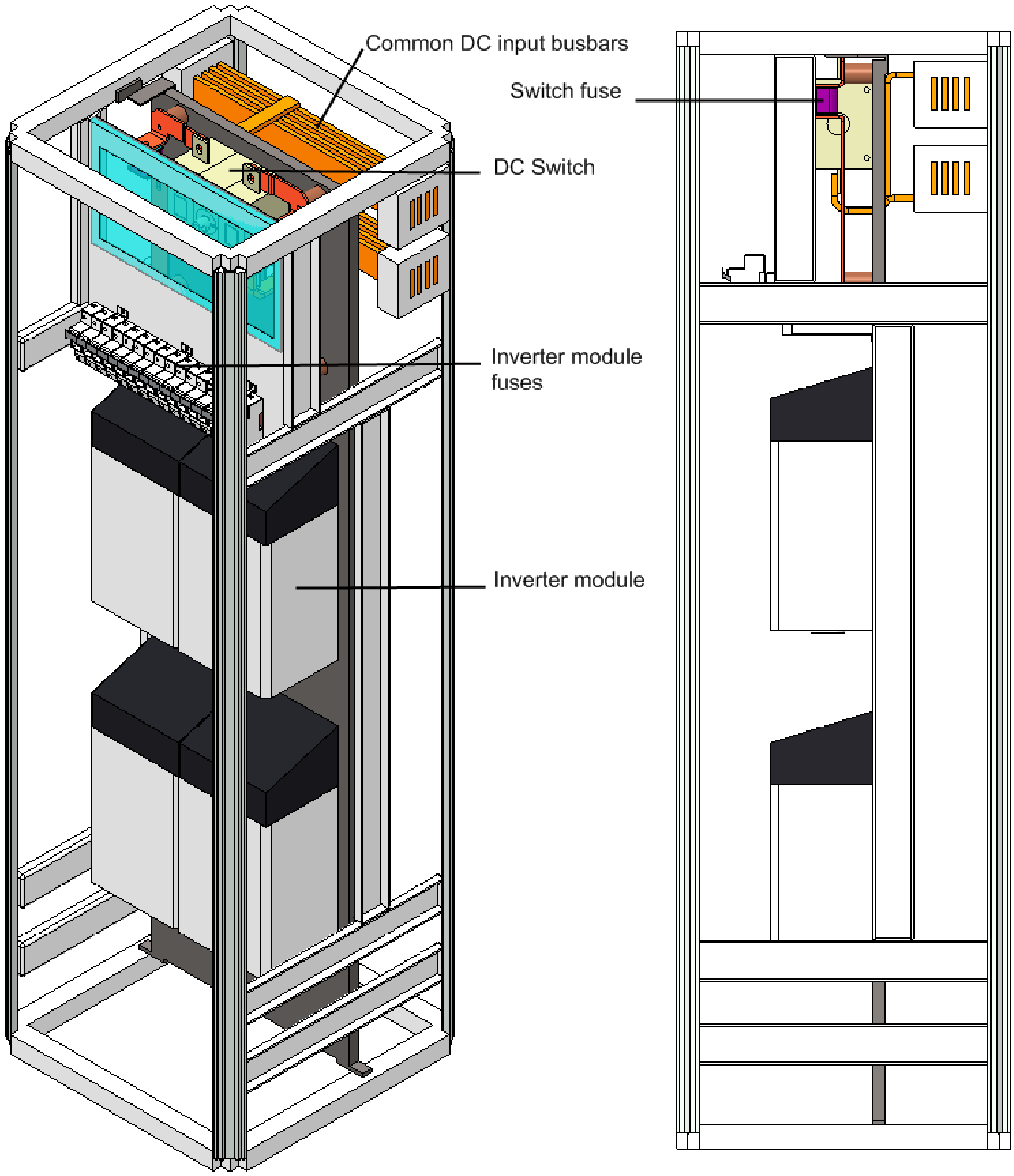


Figure 20, Simulation cabinet components

6.2 Inverter modules

The simulation components that changed the most compared to the original CAD-models were the inverter modules. Normally the inverter modules have complex features and are constructed of multiple parts from circuit boards to heat sinks, which would make the simulation process slow. When simplifying this design, it is important that the simulation results are still accurate after the simplification of the model.

The inverter module simulation models were simplified to 4 different components, which are a frame, an air guide, a fan and a porous medium block. The frames have the same measures as the original CAD-models, but instead of being constructed of many separate sheet metal pieces, the simulation frames were done with one simple part. All the components inside the frame were replaced by a porous medium block, which was given correct pressure drop values from the test done in ABB wind tunnel and heat loss values from technical data table of the inverter module manual. The simulation model of an R4i inverter module can be seen in figure 21.

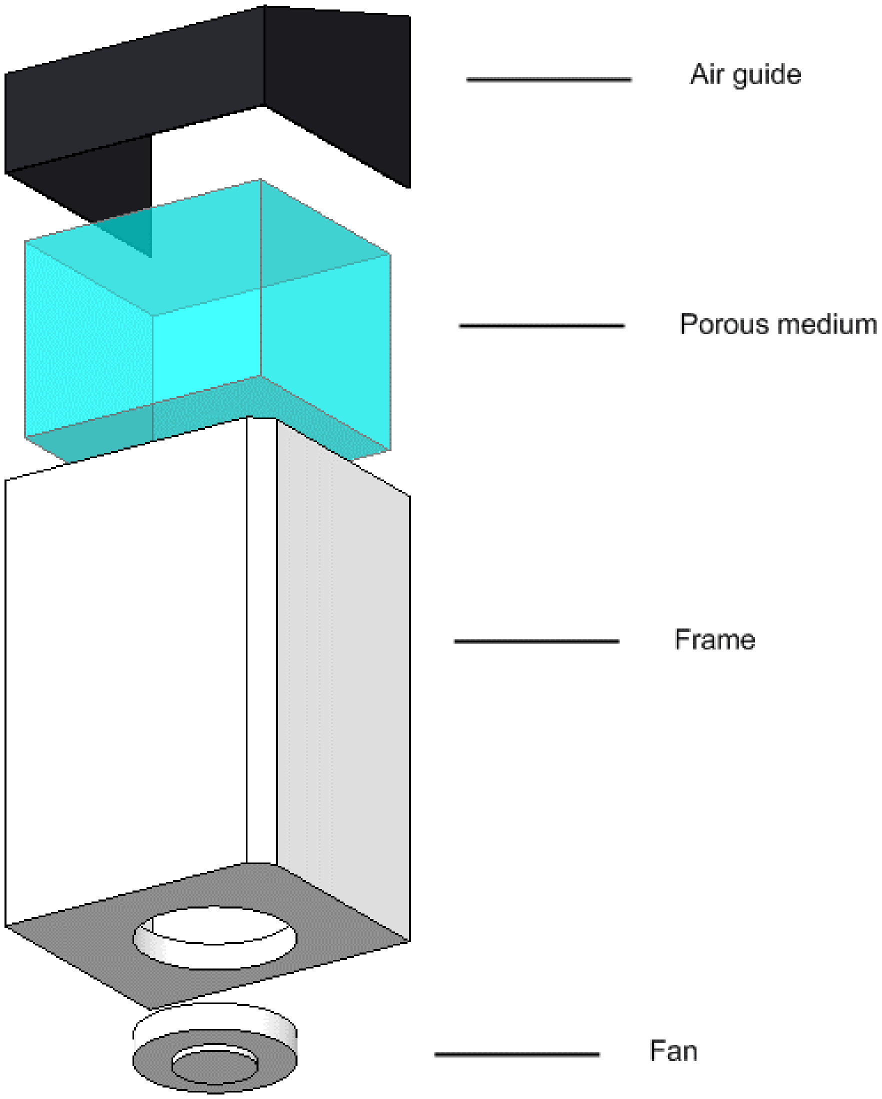


Figure 21, Exploded view of R4i inverter module simulation model

The airflow through the modules is generated by the module fans, which can be simulated by giving the fan data from the manufacturer of the fans to FloEFD. When the real inverter modules are operating, the airflow from the fan is slowed down by dynamic pressure losses created by the components inside module. To achieve realistic airflow volumes inside the simulation cabinets, are the pressure loss values from the tests set to the porous medium of the modules with FloEFD during the simulations. The pressure loss curves for the R1i and R4i inverter modules are presented in test results chapter 7.1.

The power loss values for the R1i and R4i modules were taken from the ACS880-104 hardware manual and set to the porous medium in FloEFD. The highest power loss for R1i inverter frames was 90 W while R4i modules reached 750 W. The R1i simulation cabinet included 8 inverter modules, so the total power loss generated by the inverters was 720 W. Maximum amount of R4i modules in the simulated cabinet is four units, which created a total power loss of 3000 W.

6.3 Roof fan model

To start the roof fan simulations, a simplified model was created of the roof fan kit provided by ABB. The measures for the fan and the fan box were taken from the existing CAD model, and then the simplified model was created. The simulation fan box design can be seen in figure 22.

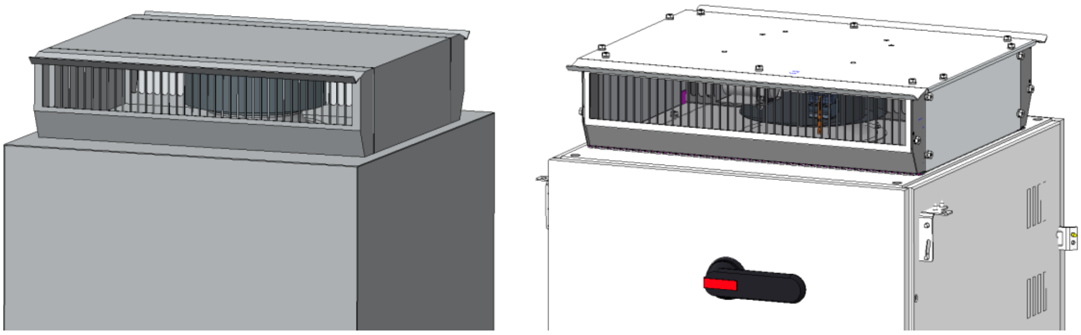


Figure 22, Simulation and original CAD-models for roof fan frame on top of Rittal TS8 cabinet

To enable fast simulation process, the roof fan outlet design was simplified as much as possible. The casing was done from a few simple parts, leaving out all small components such as screws and small mechanical and electrical components that the fan included. In the end, the roof fan simulation model included 9 parts in total whereas the normal CAD-model includes 143 objects. This means that the simulation model is made only with 6% of the parts of the normal model, which significantly decreases the amount of calculation needed for the simulations.

The fan used in 600 mm wide IP-42 class cabinet is R3G225-RD05-03 provided by Ebmpapst. Fan curve data was recorded from the manufacturer tables, and moved to FloEFD for the simulations. The simulation model of the fan can be seen on figure 23.

FlowEFD lets the user to define air inlet and outlet of the fan, by selecting surfaces. The green arrows demonstrate the air exiting the fan, while air inlet is set on the bottom surface of the fan model.

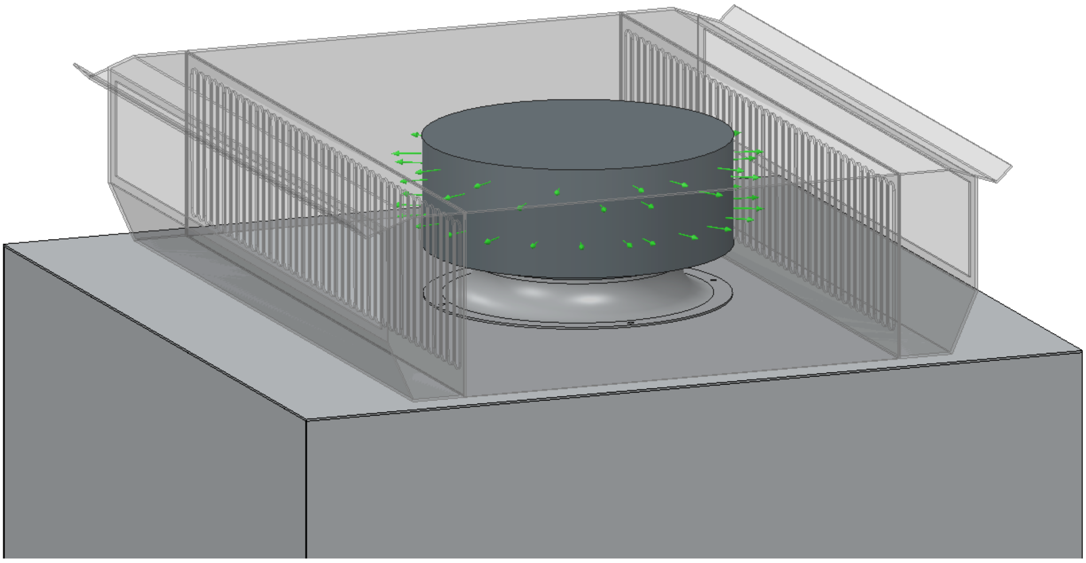


Figure 23, Roof fan in simulation model

Since the simulation model of the fan only required surfaces for air inlet and outlets to function, the simulation model was very light compared to the real fan seen in figure 24. Complex shapes such as fan blades were left out, but realistic results were still gained with the manufactures data that was input to FloEFD simulation model.

Figure 24, photo of the roof fan R3G225-RD05-03

6.4 Roof outlet without a fan

The air outlet without a fan has the same casing than with the fan that was seen in the previous chapter, the only difference is that the bottom plate has a large square hole instead of the round hole for the fan. This outlet relies on natural convection and the forced convection provided by the inverter module fans. The simulation model of the outlet is demonstrated in figure 25. Normally this outlet is only recommended for ACS880-104 module sizes that are greater than the R1i to R4i frames that are simulated in this thesis.

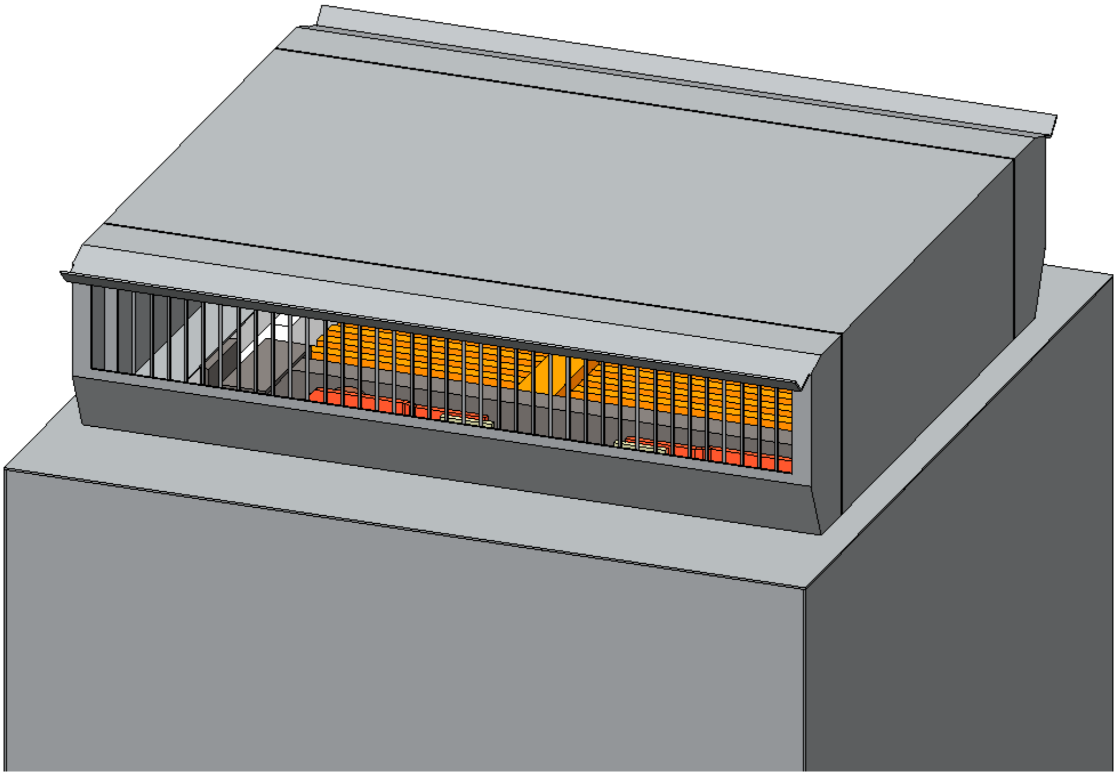


Figure 25, Roof outlet without a fan

Since the casing of the roof outlet does not differ with or without the fan, the same parts were used for the simulation assemblies.

6.5 Elevated roof design

The elevated roof design is a simple solution, where the cabinet roof plate is raised by four support bars allowing the hot air to exit. Rittal provides these support bars for the TS8 cabinet model which is studied in this thesis. The main advantage of this design compared to the outlet without a fan is that the design is much more simplistic, making it also cheaper.

Due to the simple design of this outlet, the simulation model did not require much modelling as it can be seen on figure 26. The simulations with this outlet were done in two different ways – first with the normal design and then with the side holes blocked. The reason behind simulations with the side holes blocked is that the Rittal cabinets are often installed side by side without any space between. If all the cabinets installed in the same row have a similar elevated outlet, the hot air would mix with other cabinets from the outlet sides, or the air could start to circulate between the enclosures which would disturb the cooling. This can be prevented simply by blocking the outlet sides, which was done in the simulations.

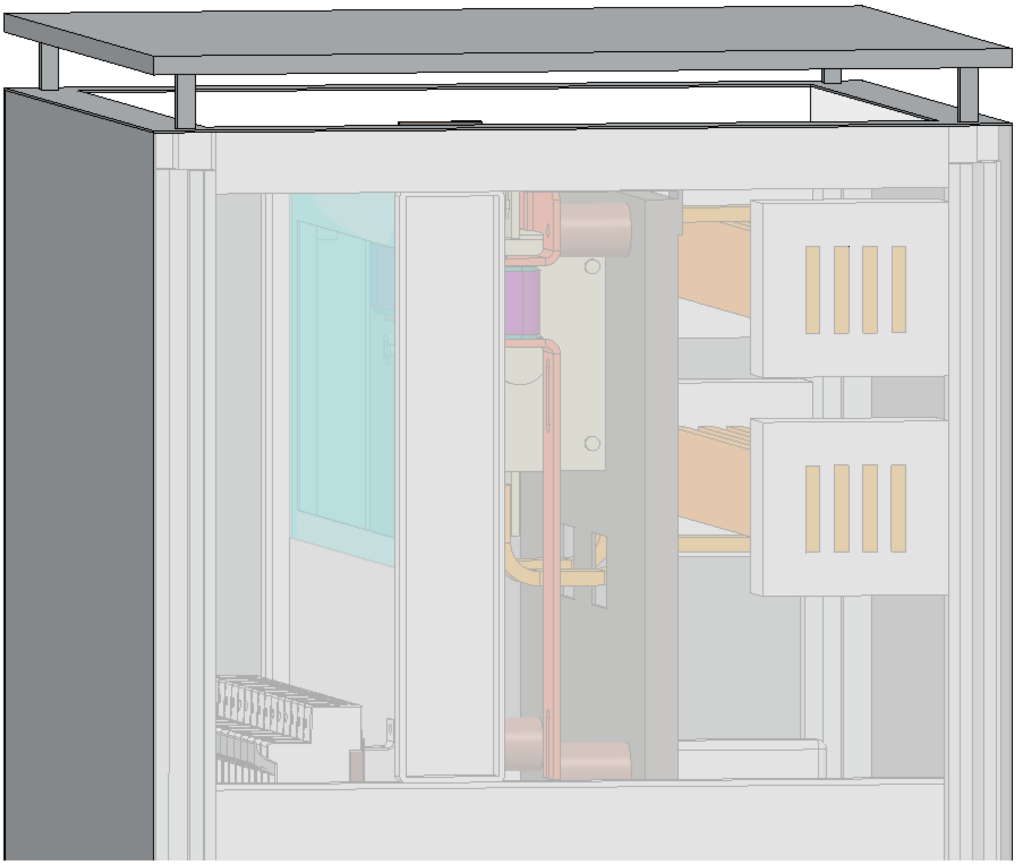


Figure 26, Elevated roof design

7 Results

7.1 Test results

The wind tunnel test results can be seen in figures 27 - 30. All modules were tested with the fan on and off. The tests results where the fan was off could be used for simulating situations where a fan is broken or the module is turned off, but since these were not in the scope of the thesis this chapter focuses on the results where the fan was operating.

The test results were recorded from the 0 static pressure point forward, forming a pressure drop curve with the volume flow increasing. The point where the pressure drop is 0 means that the pressure before and after the module is the same. At this point the volume flow through the module can be considered as the maximum that the module fan can produce in a steady environment pressure situation without external forced convection.

The R1i module was the smallest of the tested modules, and it naturally had the smallest fan. The fan type was "2410ML-05W-B60". The module had 0 pressure drop at 27 m^3/h volume flow inside the tunnel. The pressure drop chart of R1i is presented in figure 27.

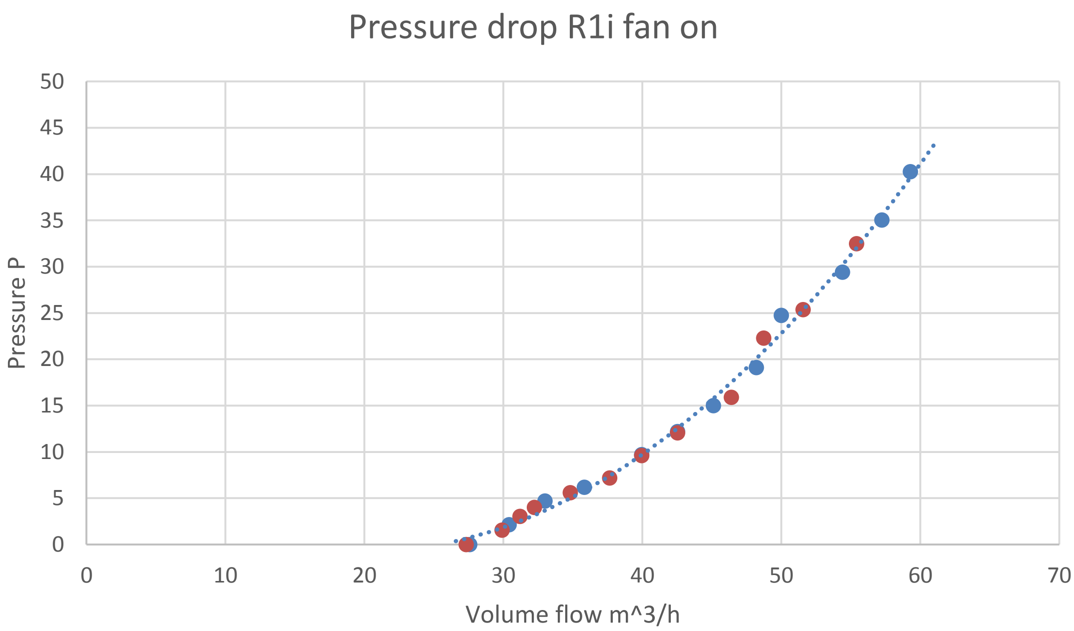


Figure 27, Pressure drop of R1i inverter module

The R2i module uses fan type “3110KL-05W-B70”. This axial fan creates 57 m^3/h through the module at 0 pressure point. By comparing figures 28 and 27, it can be seen that the R2i has approximately double the airflow compared to R1i module.

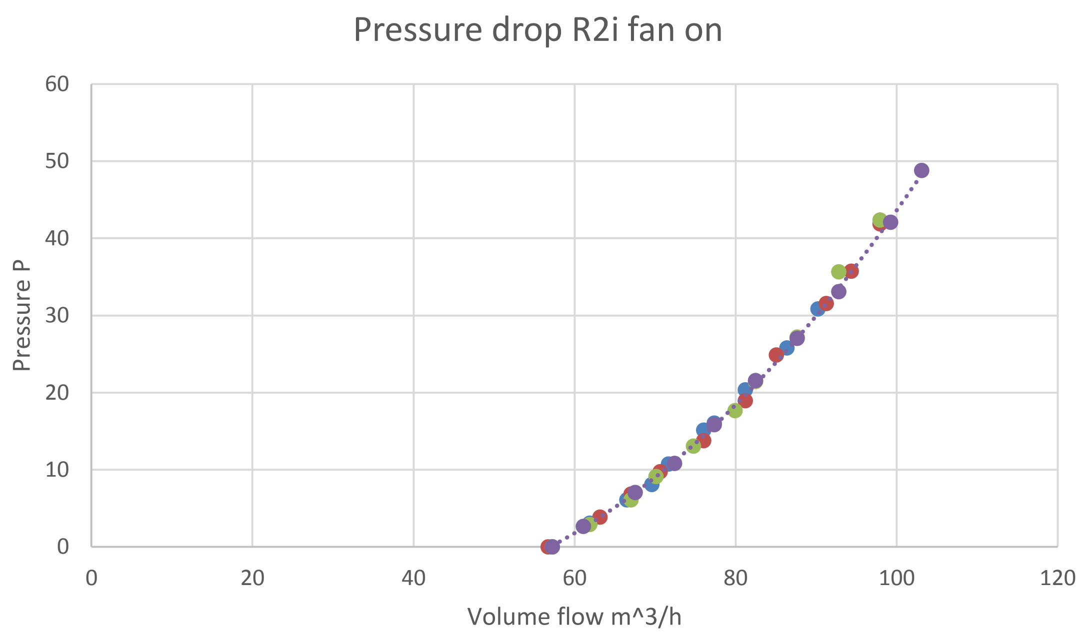


Figure 28, pressure drop of R2i inverter module

Both R3i and R4i modules use the same axial fan “PFB1224GHE”. As seen from the measurement results in figures 29 and 30, these modules have nearly the same pressure drop curve and the difference of volume flows at 0 pressure difference is minor. For R3i the volume flow at the 0 pressure difference point is 246 m^3/h while this is 258 m^3/h for the R4i module.

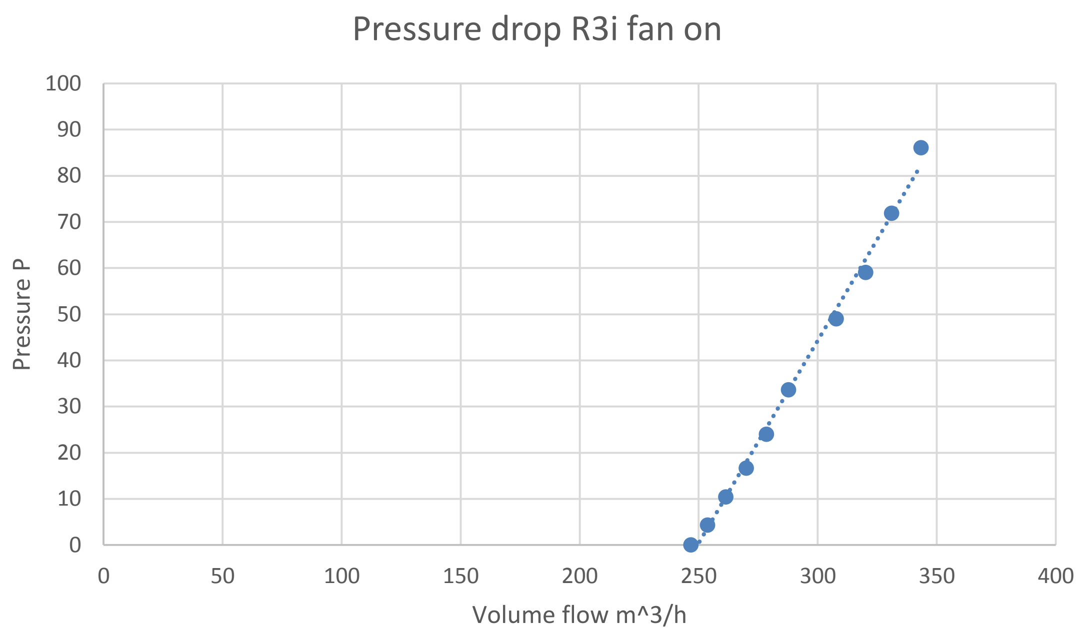


Figure 29, pressure drop of R3i inverter module

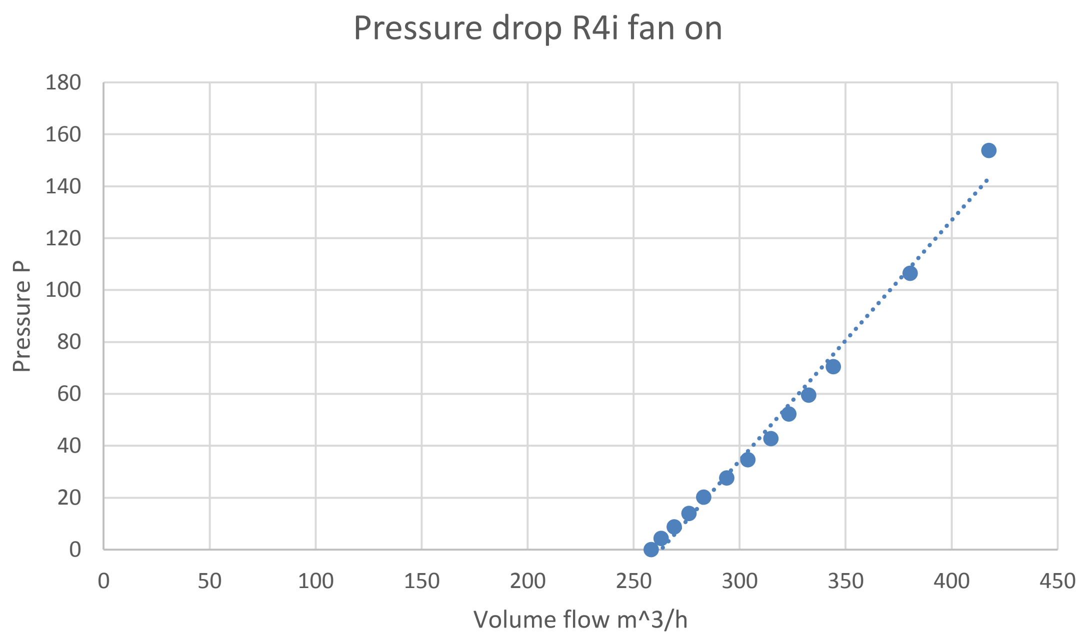


Figure 30, pressure drop of R4i inverter module

7.2 Simulation results

In this chapter, simulation results are presented on all the different variations of the studied inverter cabinets. The simulation results are divided into two main categories, which are airflow and heat load distribution inside the 600 mm wide Rittal enclosure.

7.2.1 Airflow

The airflow in each cabinet variation is shown on a cut plane, where the air speed is demonstrated with different colours, and the direction of the flow can be seen from arrows. The cut planes give a good view on how the air flows inside the cabinet, but this data is hard to analyse for comparing which design is the best. For a simple comparison, also the volume flow rate through each cabinet was calculated. As airflow through a cabinet increases, so does the convective cooling.

7.2.1.1 Cabinet with a roof fan

The airflow in Rittal cabinet with 4 R4i inverter modules can be seen in figure 31. The air velocity reaches the highest point at the roof fan intake area where air travels approximately 14,9 m/s. The second highest velocities can be found from the inverter modules and from the roof outlet, where module fans and the roof fan produce velocities between 4 – 6 m/s.

Some circulation in the airflow can be found from the cabinet back section, but in general the roof fan generates enough draft to guide the warm air from the inverters out of the enclosure.

Volume flow-rate through the cabinet: 790,9 m^3/h

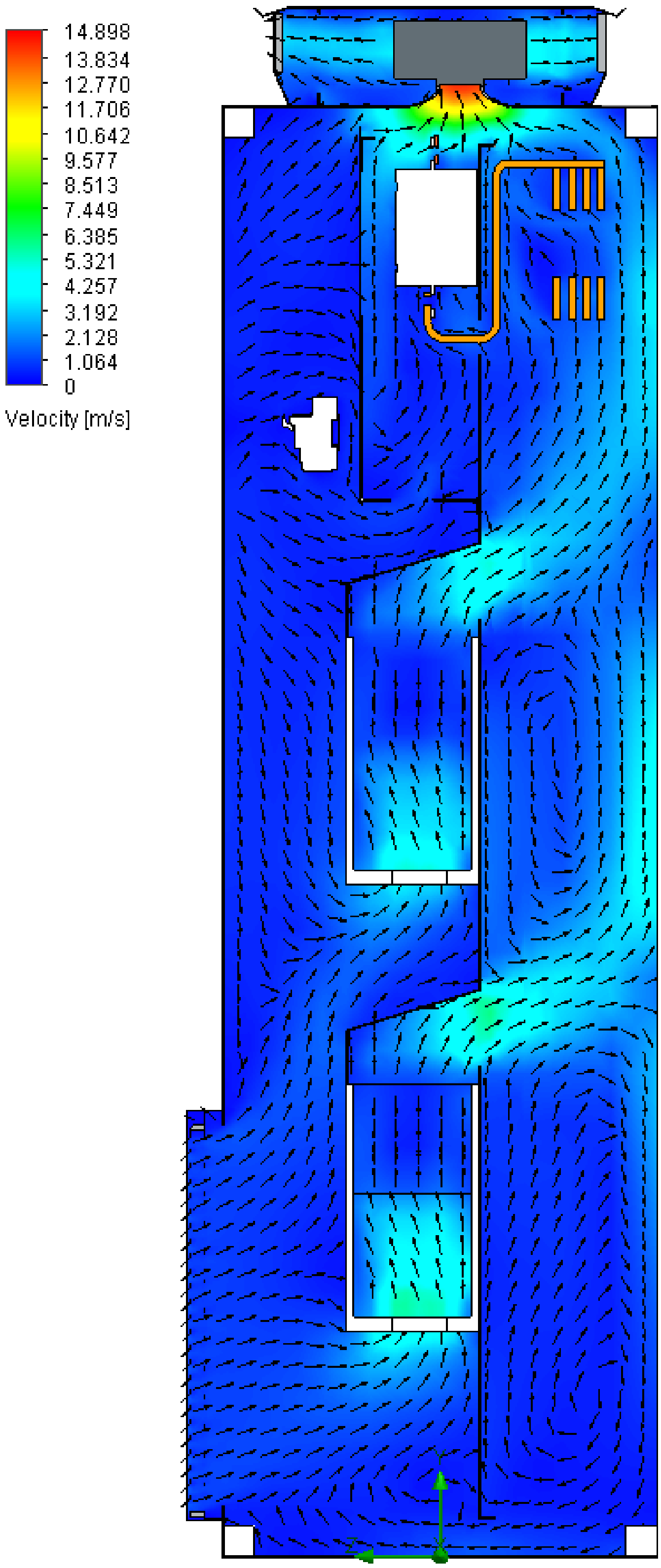


Figure 31, 4xR4i simulation air velocities, outlet with a fan

The cabinet with eight R1i inverters and an outlet with a roof fan is demonstrated in figure 32. As the roof fan is the same as with R4i modules, the highest approximate velocity is again around 14,8 m/s at the outlet intake section.

The roof fan creates a high draft inside the cabinet, and the air flows almost perfectly from the inlet to the outlet while going through all the components inside the Rittal enclosure.

Volume flow-rate through the cabinet: ***791,6*** $\boldsymbol{m^3/h}$

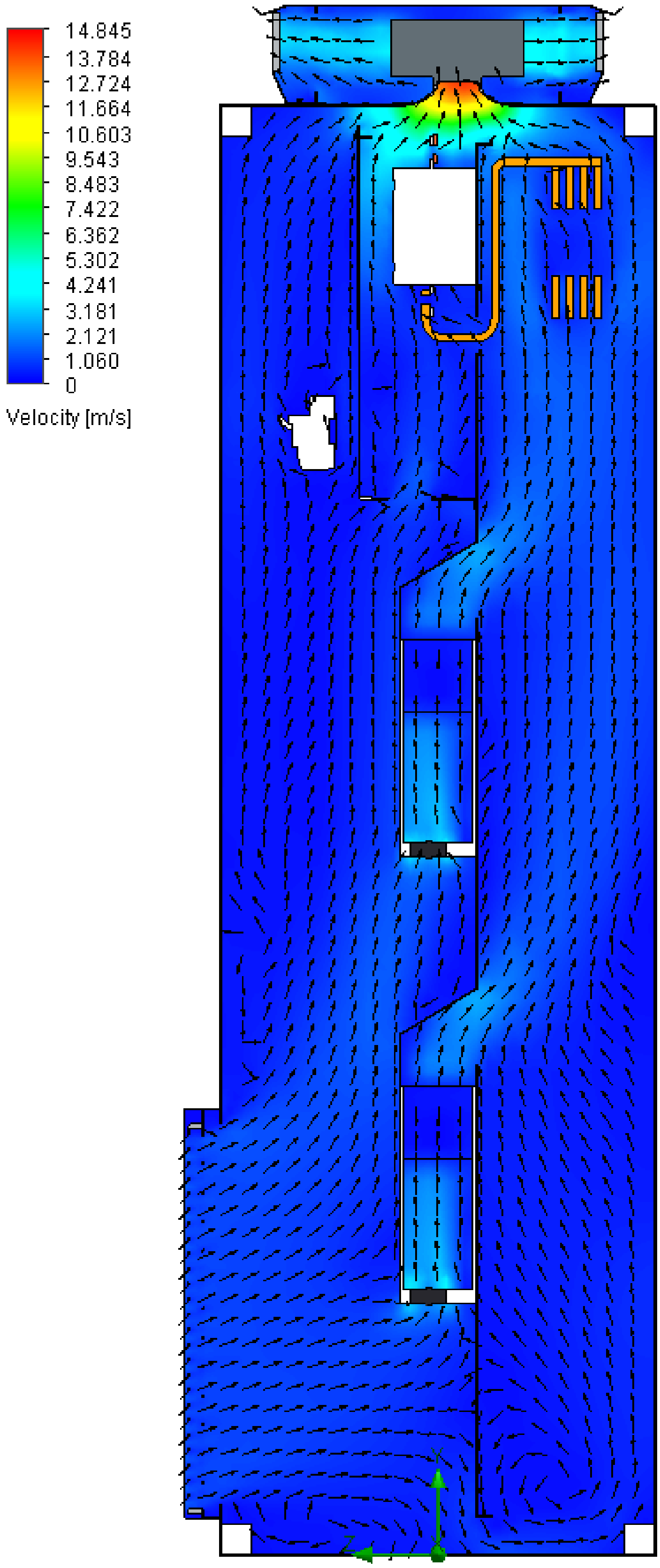


Figure 32, 8xR1i simulation air velocities, outlet with a fan

7.2.1.2 Cabinet without a roof fan

Simulation results of the Rittal cabinet with the normal ABB outlet without a roof fan are presented in figure 33. In general the air flows from to modules to the outlet in a similar way when compared to the cabinet with a roof fan.

Due to the absence of the roof fan, the highest air velocities appear around the R4i inverter modules, peaking around 5 – 6 m/s. The air circulates at the back of the cabinet between the module outlets, and also some draft from the cabinet top to the upper inverter module inlets appears. The air reaches velocities between 1 and 2 m/s at the outlet.

Volume flow-rate through the cabinet:

380,5 m^3/h

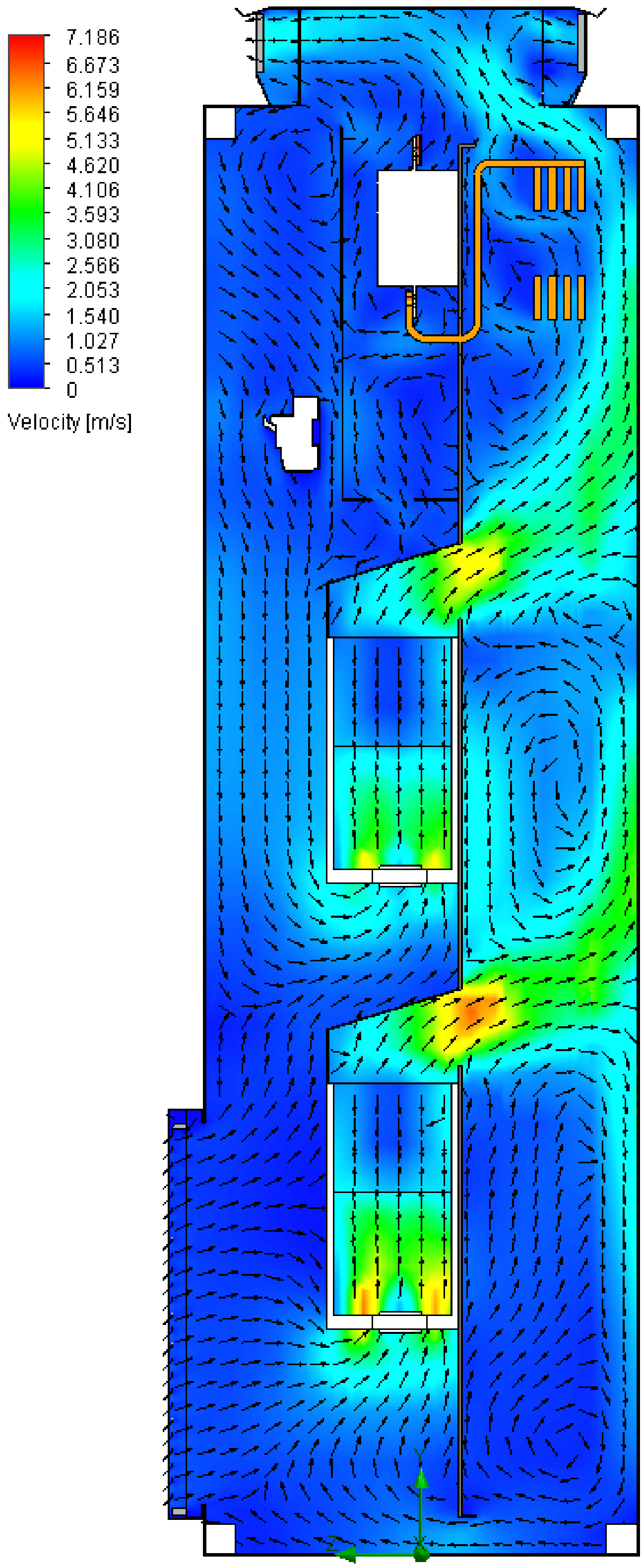


Figure 33, 4xR4i simulation air velocities, outlet without a fan

The airflow simulation results for the cabinet with small R1i inverter modules is seen in figure 34. As the R1i modules provide the only forced convection inside the cabinet, the airflow is mainly focused to the back section of the cabinet.

The air speed at the outlet is approximately 1 – 1.5 m/s. Around the modules the fans produce air velocities between 1.5 to 3 m/s.

Volume flow-rate through the cabinet:
205,2 m^3/h

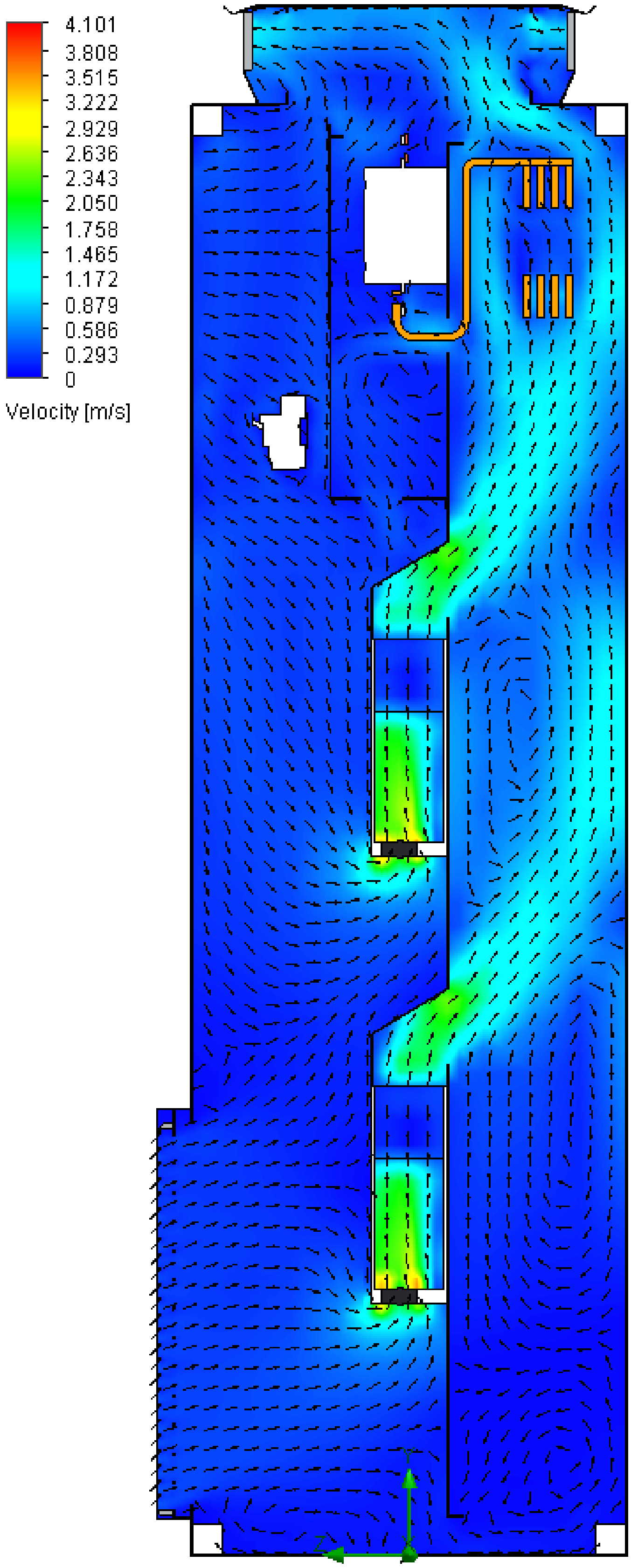


Figure 34, 8xR1i simulation air velocities, outlet without a fan

7.2.1.3 Cabinet with elevated roof

The elevated roof structure simulation with R4i modules can be seen in figure 35. The air velocities near the modules vary between 4 and 6 m/s, while inside the outlet the air velocity is at steady 2 m/s.

Some air circulation occurs at the back section of the cabinet, and a relatively strong draft brings warm air from the top of the cabinet to the upper inverter modules.

Volume flow-rate through the cabinet:
529,2 m^3/h

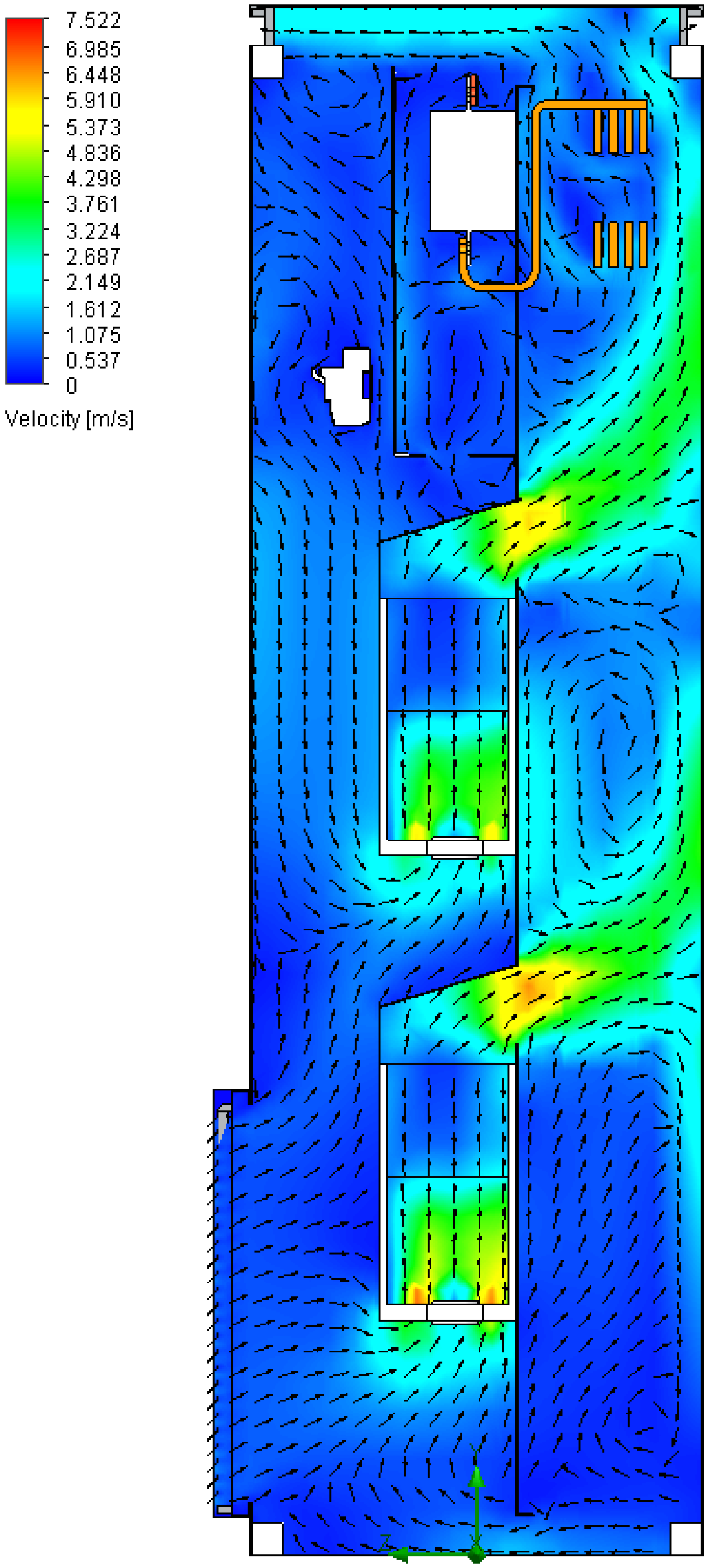


Figure 35, 4xR4i simulation air velocities, elevated roof outlet

Simulation results for the cabinet with R1i modules and an elevated roof outlet is demonstrated in figure 36. The inverter modules create a steady flow to the back section of the cabinet that moves approximately 1.3 m/s. At the outlet the flow speed is slightly slower, averaging at 1 m/s.

Volume flow-rate through the cabinet:

252,0 m^3/h

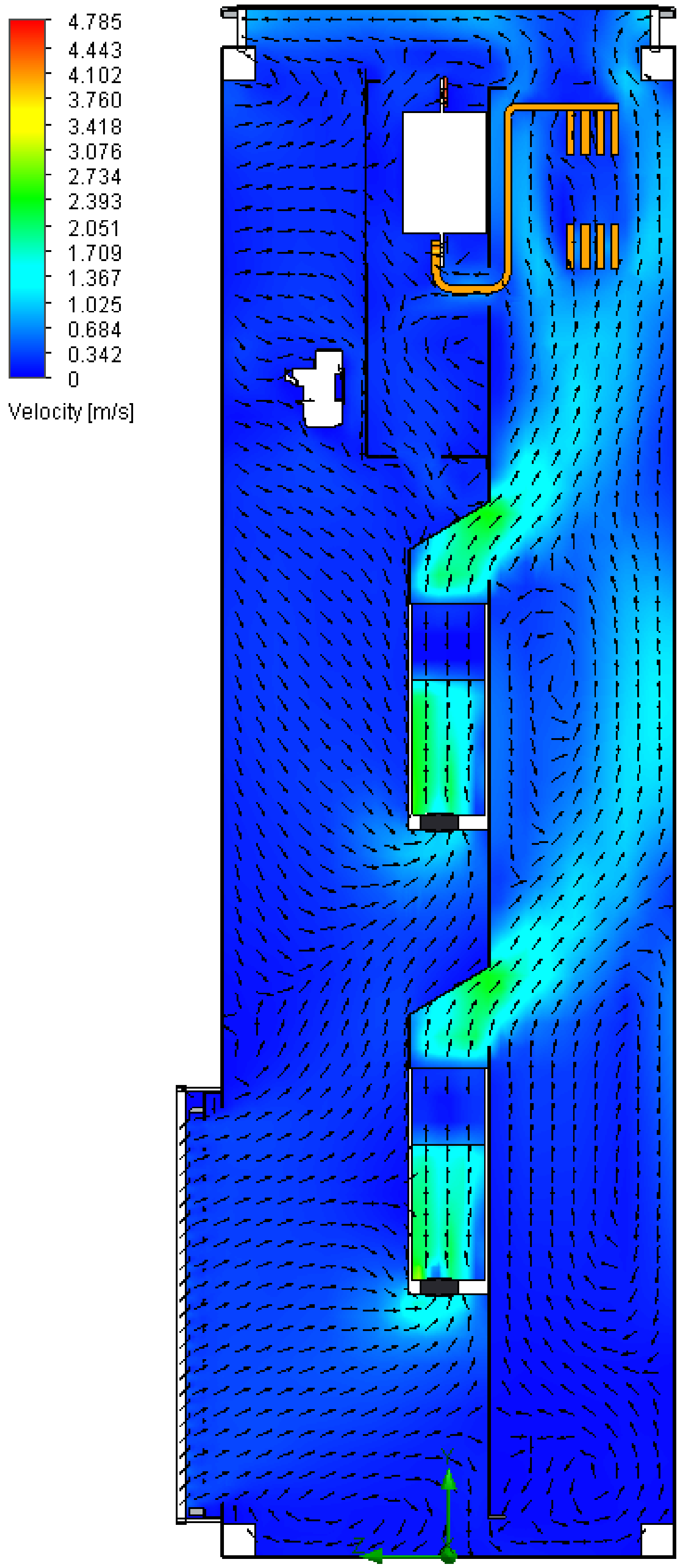


Figure 36, 8xR1i simulation air velocities, elevated roof outlet

7.2.1.4 Cabinet with elevated roof, sides blocked

The elevated roof outlet was also simulated with sides exits blocked. This simulation with R4i modules can be seen in figure 37.

The air velocities at the inverters vary again from 4 to 6 m/s, and at the top section air travels approximately at 2 meters per second. As the air moves the same speed at the outlet with the sides open and blocked, it does not surprise that the volume flowrate is significantly lower when the sides are blocked.

The air circulates heavily at the back section of the cabinet, and at the front of the enclosure the air flows downwards at 1 m/s, bringing warm air to the upper module inlets.

Volume flow-rate through the cabinet: 392,4 m^3/h

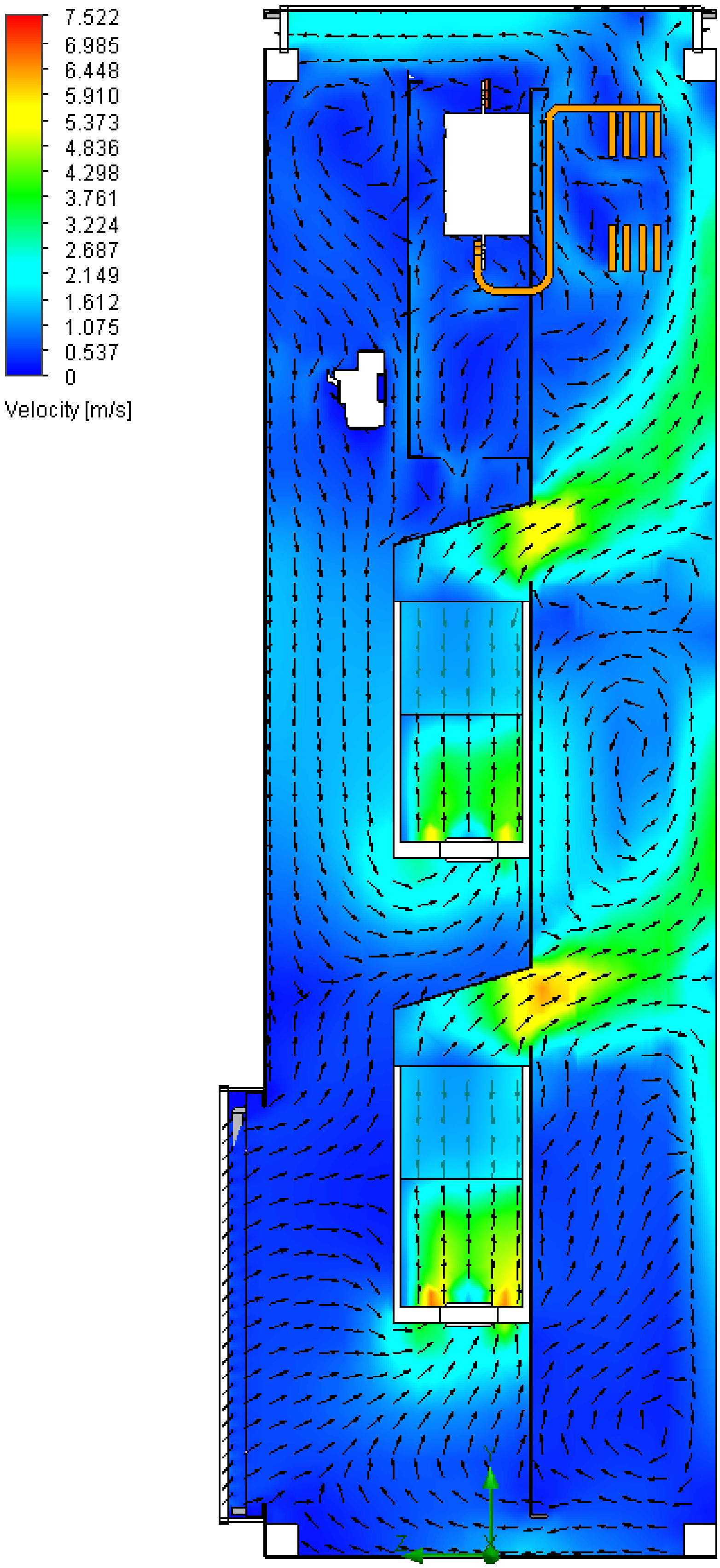


Figure 37, 4xR4i simulation air velocities, elevated roof outlet with sides blocked

The airflow in a cabinet with R1i modules and an elevated roof outlet with sides blocked is demonstrated in figure 38. The modules create a flow of 1.3 m/s at the back of the cabinet. The air velocity inside the outlet is approximately 1 m/s.

Some airflow downwards from the top of the cabinet can be seen at the cabinet front section, which brings heated air back to the modules that are installed on the higher level.

Volume flow-rate through the cabinet:

191,5 $\boldsymbol{m^3/h}$

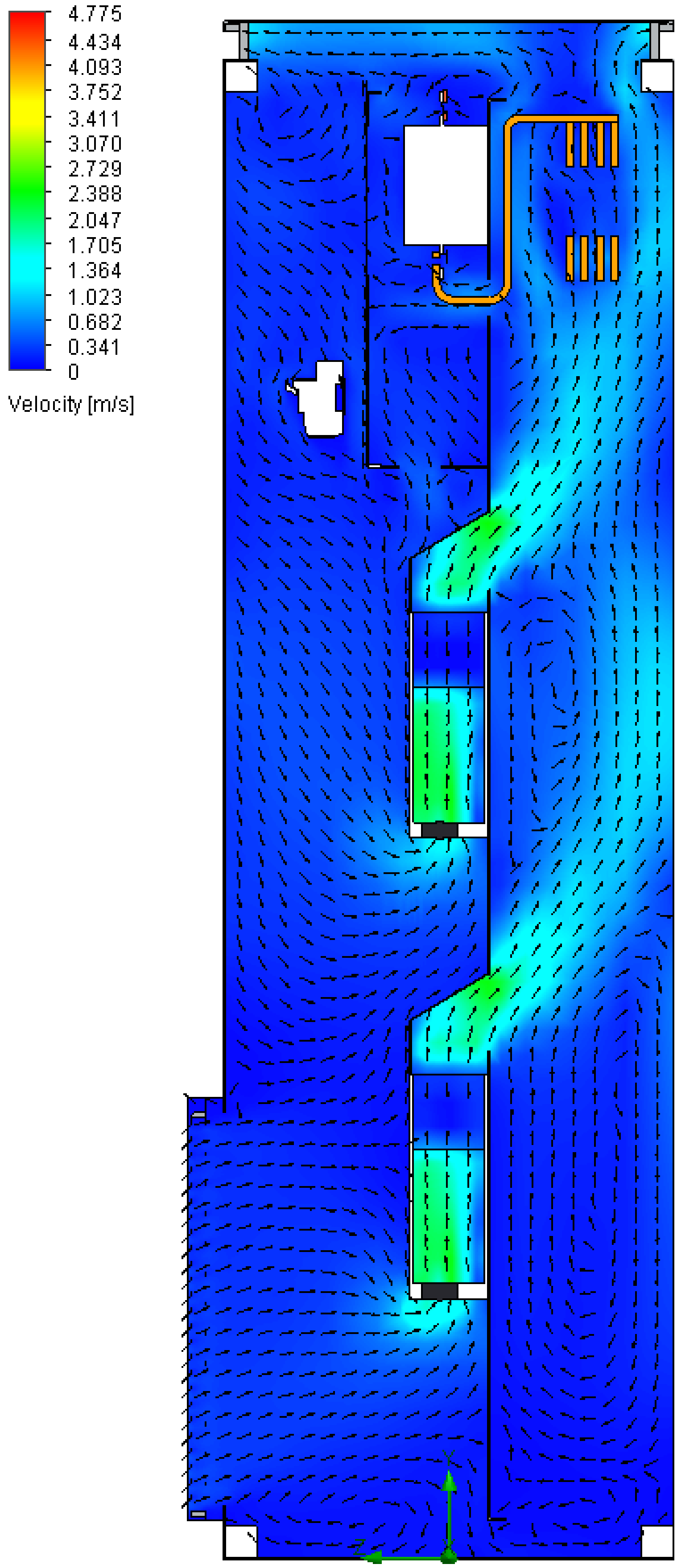


Figure 38, 8xR1i simulation air velocities, elevated roof outlet with sides blocked

7.2.2 Heat load distribution

The temperatures for all of the studied cabinet constructions were simulated and are presented in this chapter. The cabinets were simulated in a 40 °C environment, which is the highest ambient temperature allowed for the inverters without derating. To make comparison easier, a few measuring locations common for all the cabinets were chosen. The locations were named from T1 to T8 and are shown in each result figure and table. Probably the most important temperatures to look at are at the module inlets and at the cabinet outlets. The air at the module inlets should not go higher than 50 °C, and the cabinet outlet temperature quickly indicates how much the temperature raises with each individual outlet solution.

7.2.2.1 Cabinet with a roof fan

The temperatures of a cabinet with R4i modules and a roof fan are presented in figure 39. The outlet temperature is 54.3 °C, which means that difference between the air intake and out coming air is 14.3 °C. Overall the heat inside the cabinet is well distributed, as the modules receive air between 42.8 – 43.0 °C, while in the back compartment the air temperature is approximately 53 °C. The temperatures of the R4i cabinet are listed in more detail in table 2.

Simulation results for R1i cabinet are presented in figure 40 and in table 3. As the small modules do not have very high power losses, the cabinet is cooler compared to the R4i version. The outlet temperature is 44.2 °C, which means that air only heats up 4.2 °C when going through the enclosure. The R1i inverter modules air intake side temperatures are 40.1 – 40.4 °C.

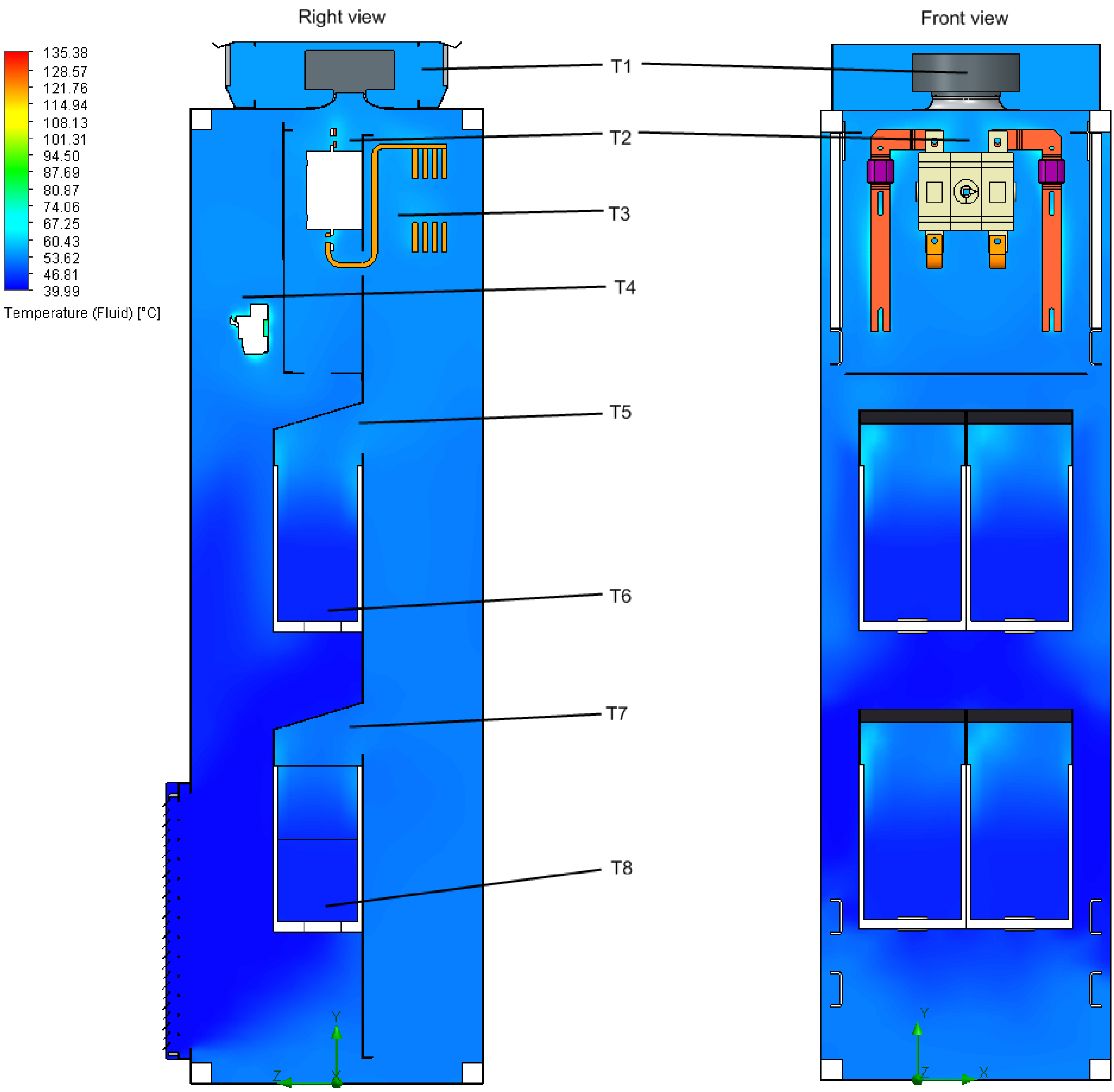


Figure 39, 4xR4i simulation temperatures, outlet with a roof fan

Table 2, 4xR4i simulation temperatures, outlet with a roof fan

	Air Temperature (°C)	Location
T1	**54,3**	Outlet
T2	**56,0**	Switch
T3	**54,3**	Common DC
T4	**52,9**	Inverter fuses
T5	**52,5**	Top module outlets
T6	**43,0**	Top module inlets
T7	**50,5**	Bottom module outlets
T8	**42,8**	Bottom module inlets

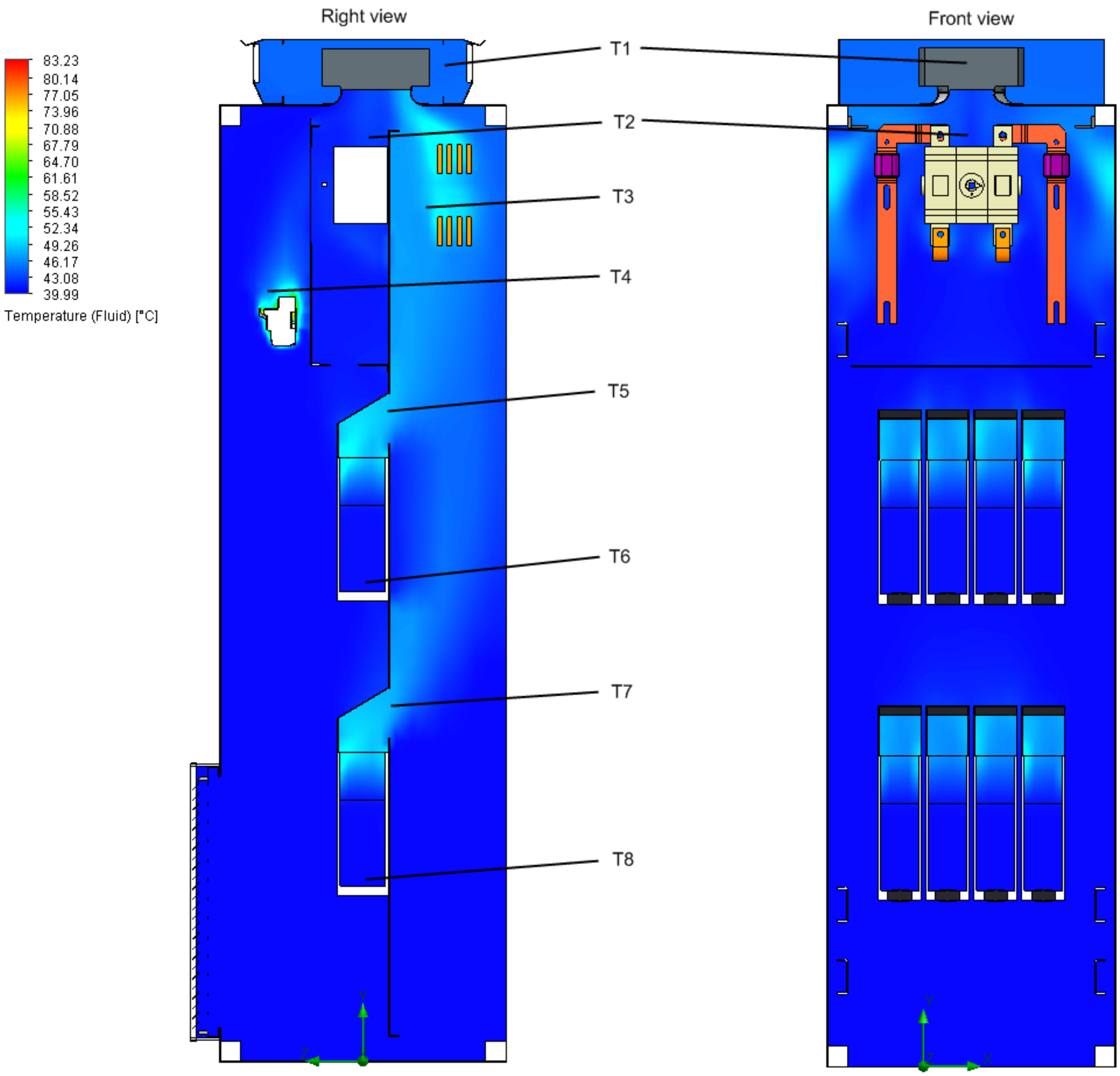


Figure 40, 8xR1i simulation temperatures, outlet with a roof fan

Table 3, 8xR1i simulation temperatures, outlet with a roof fan

	Air Temperature (°C)	Location
T1	**44,2**	Outlet
T2	**42,4**	Switch
T3	**47,1**	Common DC
T4	**46,4**	Inverter fuses
T5	**48,0**	Top module outlets
T6	**40,4**	Top module inlets
T7	**47,5**	Bottom module outlets
T8	**40,1**	Bottom module inlets

7.2.2.2 Cabinet without roof fan

Thermal simulation results for R4i cabinet with an ABB outlet without a fan are presented in figure 41. The air inside the outlet is approximately 68 °C, indicating that components inside the enclosure heated the air by 28 degrees Celsius. The intake air temperature for the inverter modules varies between 47 and 60 °C. More detail about temperatures is demonstrated in table 4.

The temperatures for R1i cabinet can be seen in figure 42. As the small modules do not produce as much heat as the R4i modules, the outlet temperature only raises to 53.8 °C. The bottom inverters receive cool intake air at 40.1 Celsius, but the top modules have a significantly higher intake temperature which averages at 48,2 Celsius. More information for the temperatures of the R1i cabinet can be found from table 5.

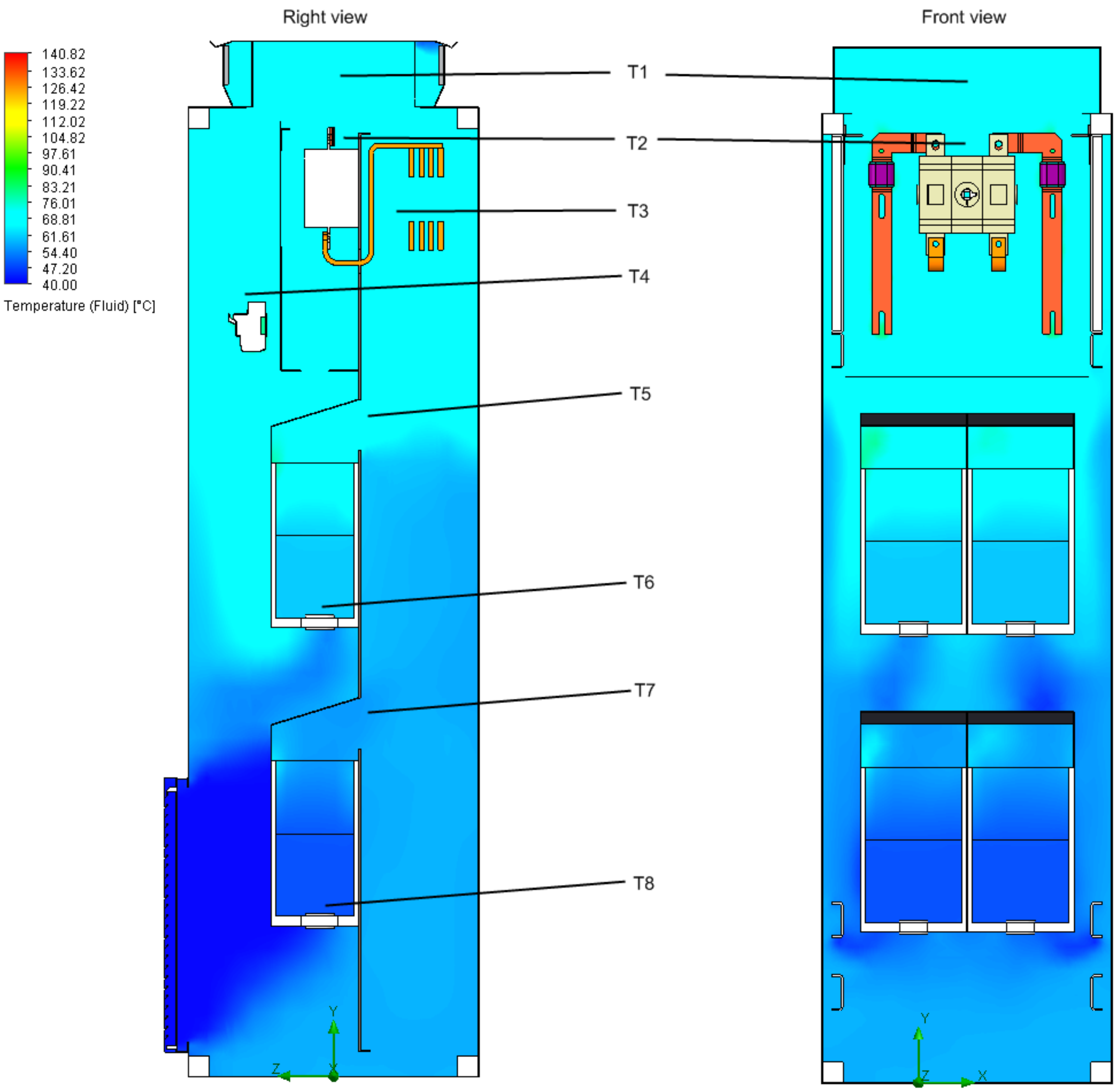


Figure 41, 4xR4i simulation temperatures, outlet without a roof fan

Table 4, 4xR4i simulation temperatures, outlet without a roof fan

	Air Temperature (°C)	Location in cabinet
T1	**68,1**	Outlet
T2	**69,5**	Switch
T3	**67,0**	Common DC
T4	**68,3**	Inverter fuses
T5	**69,5**	Top module outlets
T6	**59,6**	Top module inlets
T7	**55,2**	Bottom module outlets
T8	**47,6**	Bottom module inlets

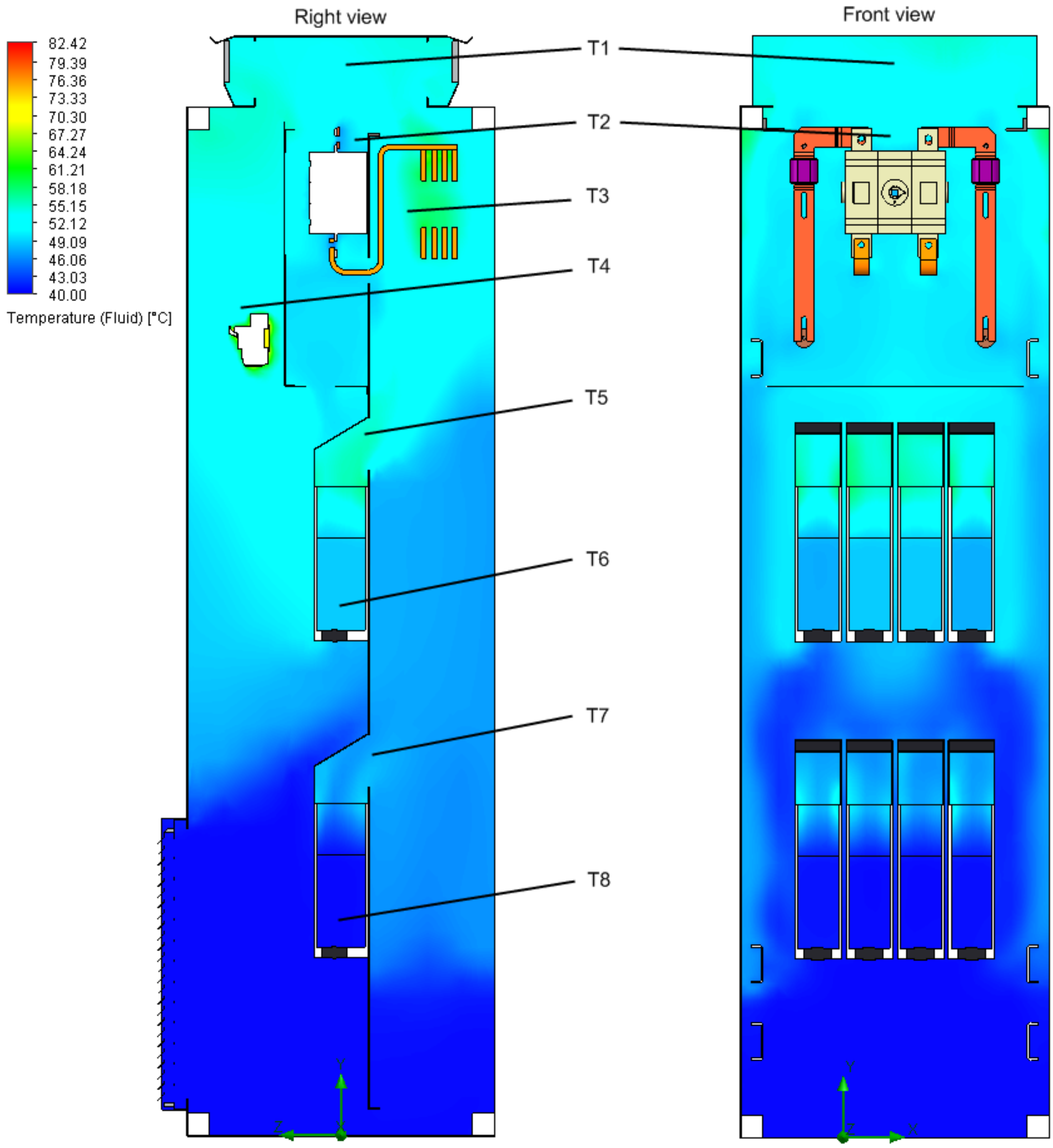


Figure 42, 4xR4i simulation temperatures, outlet without a roof fan

Table 5, 4xR4i simulation temperatures, outlet without a roof fan

	Air Temperature (°C)	Location
T1	**53,8**	Outlet
T2	**50,0**	Switch
T3	**54,4**	Common DC
T4	**51,4**	Inverter fuses
T5	**54,9**	Top module outlets
T6	**48,2**	Top module inlets
T7	**47,7**	Bottom module outlets
T8	**40,1**	Bottom module inlets

7.2.2.3 Cabinet with elevated roof

The elevated roof outlet thermal simulation results are presented in figures 43 and 44. This simulation was done with all 4 sides of the outlet open, allowing the air to exit freely to every horizontal direction. With R4i modules the outlet temperature is approximately 60.0 °C, indicating 20.0 °C gain between the inlet and the outlet. The module inlet air temperature is between 45 and 52 Celsius degrees.

The small R1i inverter module cabinet reached 51.6 °C inside the outlet, meaning 11.6 °C temperature increase as air goes through the enclosure. The intake air temperature for the inverter modules varied between 40.1 and 44.8 °C. More temperature data is presented in tables 6 and 7.

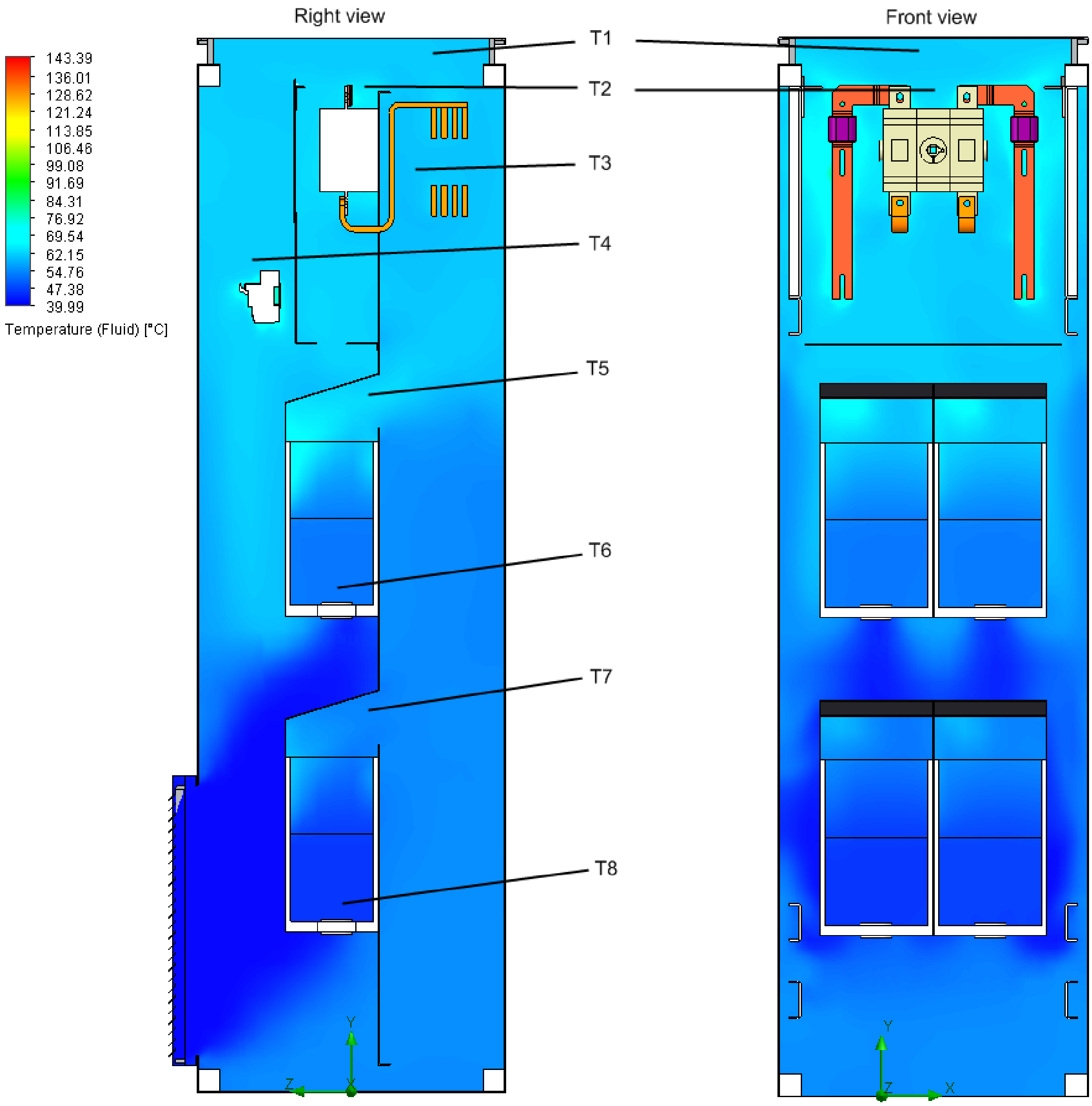


Figure 43, 4xR4i simulation temperatures, elevated roof outlet

Table 6, 4xR4i simulation temperatures, elevated roof outlet

	Air Temperature (°C)	Location
T1	**60,0**	Outlet
T2	**63,6**	Switch
T3	**59,2**	Common DC
T4	**60,6**	Inverter fuses
T5	**60,8**	Top module outlets
T6	**51,7**	Top module inlets
T7	**52,8**	Bottom module outlets
T8	**45,1**	Bottom module inlets

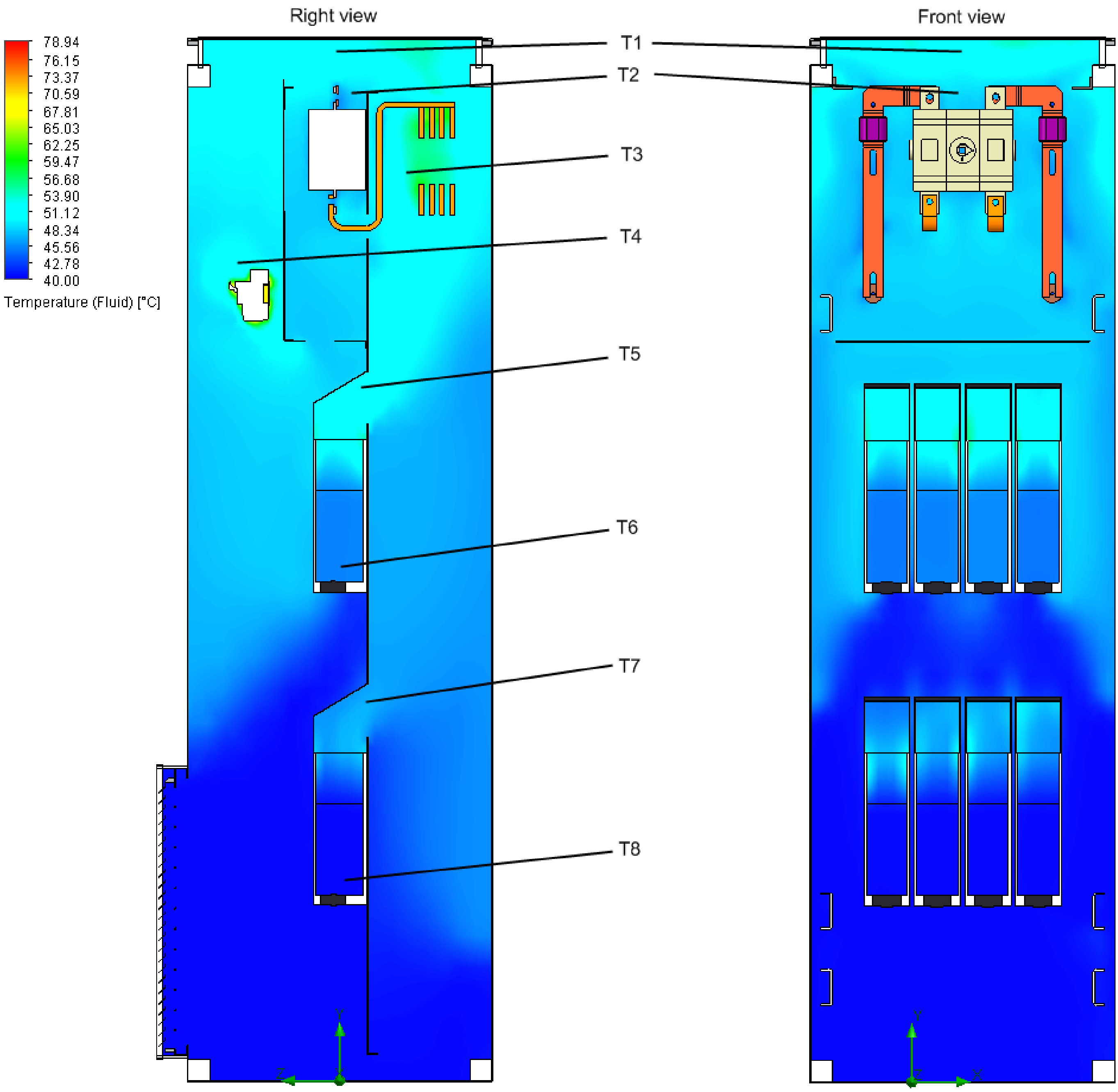


Figure 44, 8xR1i simulation temperatures, elevated roof outlet

Table 7, 8xR1i simulation temperatures, elevated roof outlet

	Air Temperature (°C)	Location
T1	**51,6**	Outlet
T2	**49,3**	Switch
T3	**53,8**	Common DC
T4	**50,7**	Inverter fuses
T5	**51,2**	Top module outlets
T6	**44,8**	Top module inlets
T7	**46,4**	Bottom module outlets
T8	**40,1**	Bottom module inlets

7.2.2.4 Cabinet with elevated roof, outlet sides blocked

Final thermal simulations were done with the elevated roof design, while blocking the side exits of the outlet. The R4i module results are demonstrated in figure 45. The outlet reached temperature of 66.9 °C which indicates 26.9 °C temperature increase for the cooling air. Air temperature at the inlets of the R4i modules varied between 59.7 and 46.6 Celsius degrees. Other temperatures for the R4i cabinet can be found from table 8.

The outlet temperature for the R1i inverter modules were 56.8, as table 9 states. This indicates 16.8 Celsius degree increase between the entering and exiting cooling air. The modules received cooling air at temperatures from 40.1 to 55.4 °C. The overall heat distribution of the R1i cabinet can be seen in figure 46.

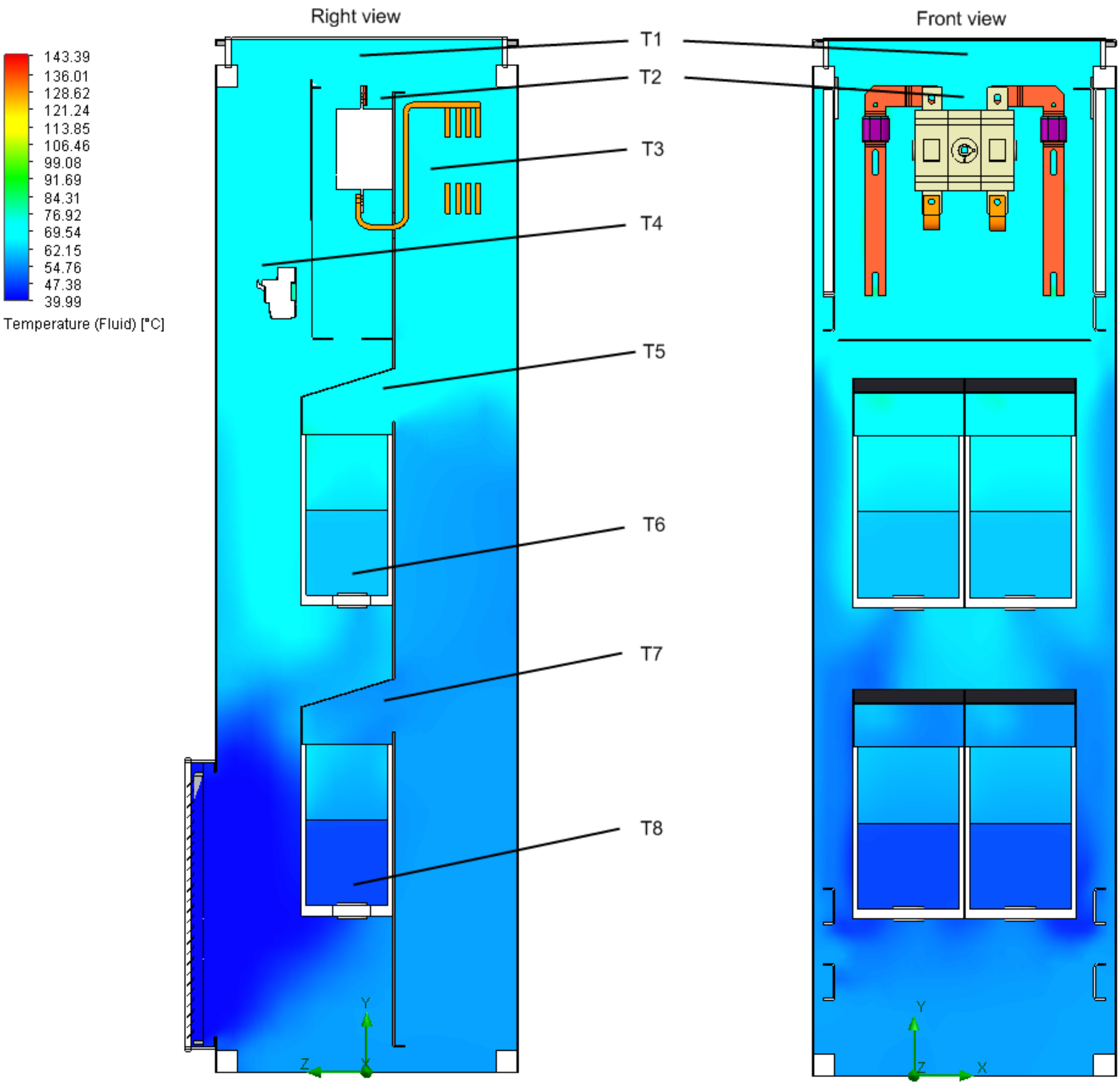


Figure 45, 4xR4i simulation temperatures, elevated roof outlet with sides blocked

Table 8, 4xR4i simulation temperatures, elevated roof outlet with sides blocked

	Air Temperature (°C)	Location
T1	66,9	Outlet
T2	69,9	Switch
T3	65,1	Common DC
T4	67,4	Inverter fuses
T5	70,0	Top module outlets
T6	59,7	Top module inlets
T7	54,5	Bottom module outlets
T8	46,6	Bottom module inlets

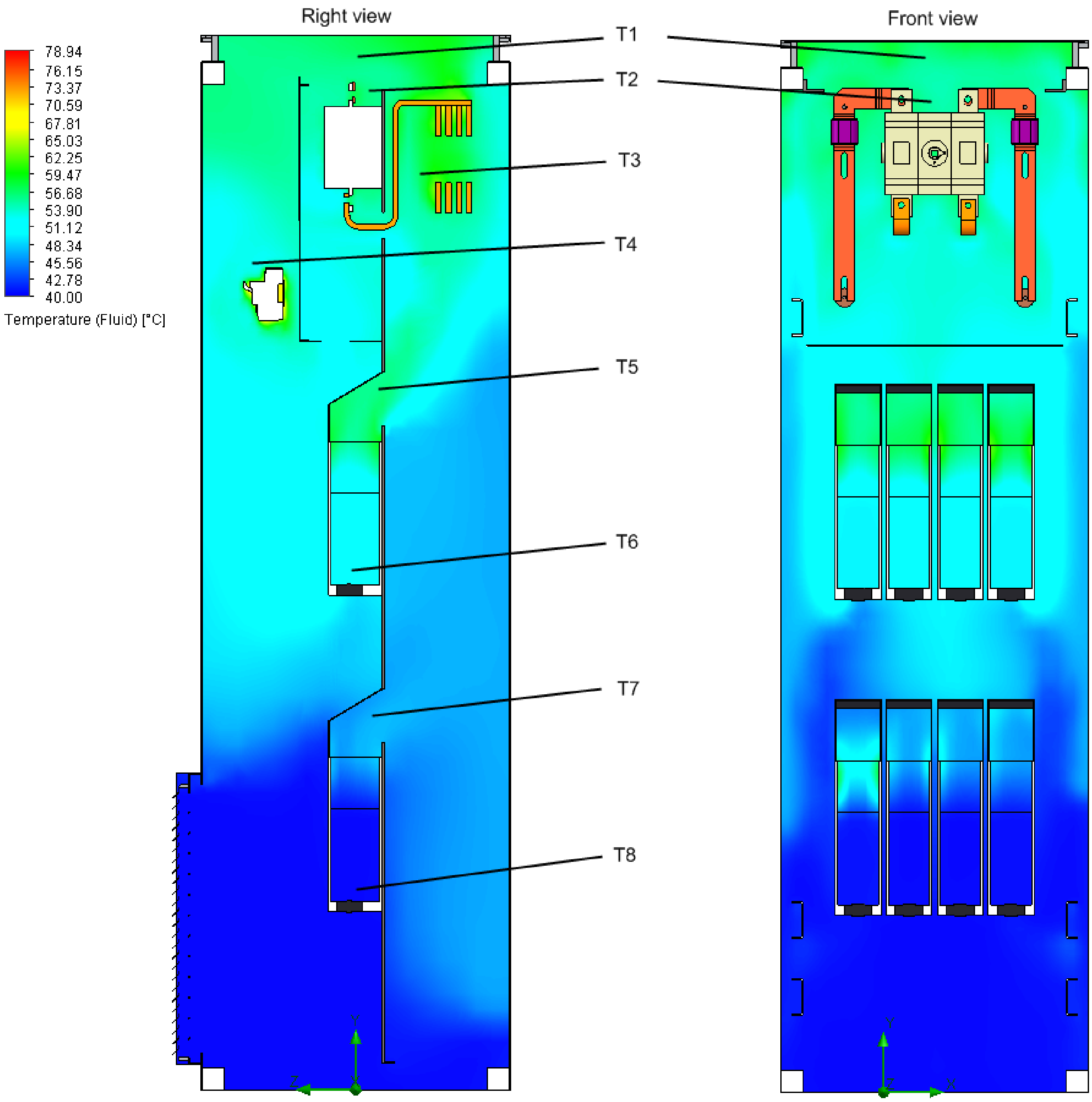


Figure 46, 8xR1i simulation temperatures, elevated roof outlet with sides blocked

Table 9, 8xR1i simulation temperatures, elevated roof outlet with sides blocked

	Air Temperature (°C)	Location
T1	56,8	Outlet
T2	55,4	Switch
T3	55,6	Common DC
T4	52,8	Inverter fuses
T5	55,4	Top module outlets
T6	49,5	Top module inlets
T7	46,1	Bottom module outlets
T8	40,1	Bottom module inlets

7.3 Error sources in testing and simulations

Both the testing process and the simulations presented in this thesis include some risk of errors that should be taken into consideration when going through the results. The wind tunnel test setup equipment has approximately an accuracy of $\pm 5\%$ according to Timo Koivuluoma (Koivuluoma, 2000). The simulation software accuracy depends mostly on the given input values.

In addition to the individual errors caused by the wind tunnel test equipment, some inaccuracy may occur inside the wind tunnel testing space where the inverter modules were installed. As the airflow and pressure drop were measured, the testing space was isolated into two compartments with duct tape and cardboard. Even though these materials are usually enough for blocking airflow, a risk exists that the air flows through a small gap in the sealing making the results inaccurate.

The simulation result accuracy depends on multiple factors. Probably the most visible source for error is the simplification of the simulation models, which can be seen especially in the inverter module designs. All the power losses in the simulation models were inserted inside the inverters in the porous medium, but in reality the losses would not distribute as perfectly through the cooled area inside the modules. However, as the simulation focused on the air flow and heat inside the cabinet, the error in the module heat distribution should not have a great impact in the final results.

Another factor causing inaccuracy in the simulations is that the input values for components such as fans and fuses were taken from the manufacturers. The manufacturer results may have been achieved in optimal environmental conditions that could vary from the simulated space. Another possibility is that the specifications given by the manufacturer include a safety buffer to insure that the product works, which could for example make the simulation fans slightly less efficient in comparison to reality.

As the simulations included only two different cabinet base variations, the comparison of different outlet performances is relatively accurate. If for example some of the R1i cabinet input values was incorrect, the cabinet base construction and the error would be the same with all the three outlets. Therefore the outlet with best performance would still provide the best results in the end, even if temperature or airflow inside the cabinet was slightly different from the real values.

8 Conclusions and recommendations

The simulations provided results on airflow through the cabinet, showing the quantity of convective airflow each outlet solution provides. Another simulated factor was the temperature inside the cabinet. When looking at the results from figure 47, it is clear that the outlet with a fan produces most airflow as expected. Second highest volume flows are provided by the elevated roof outlet. Least volume flow was gained with the outlet without a fan and with the elevated roof outlets which had side holes blocked.

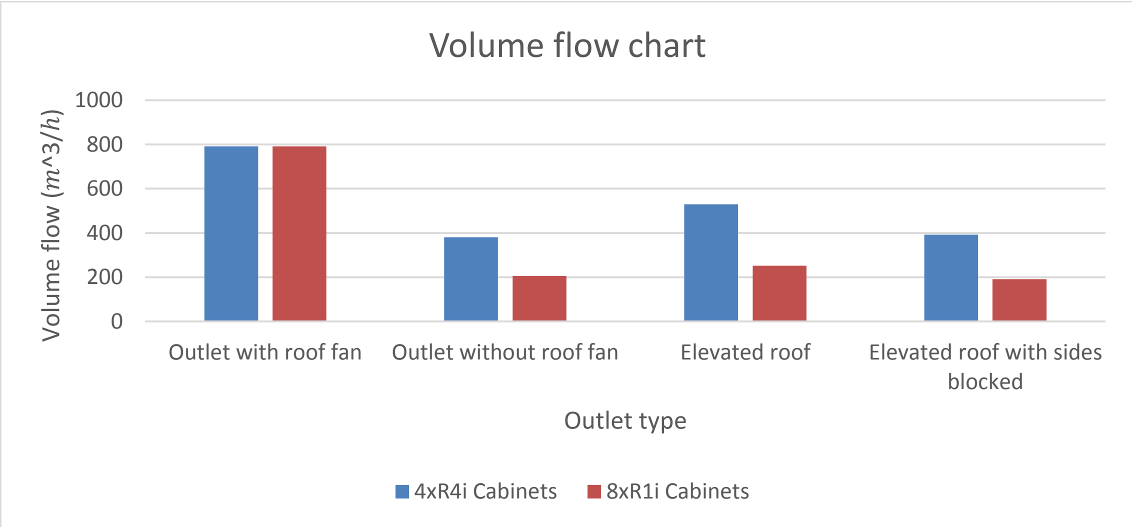


Figure 47, volume flow chart

A comparison of the temperature increase between all the simulated cabinets and outlet variants is presented in figure 48. The coolest cabinets according to these results are the ones installed with a roof fan outlet. Second least temperature gain was achieved with the open elevated roof outlet, while the normal outlet without a fan and the elevated roof outlet with sides blocked proved to be worst solutions in terms of air cooling.

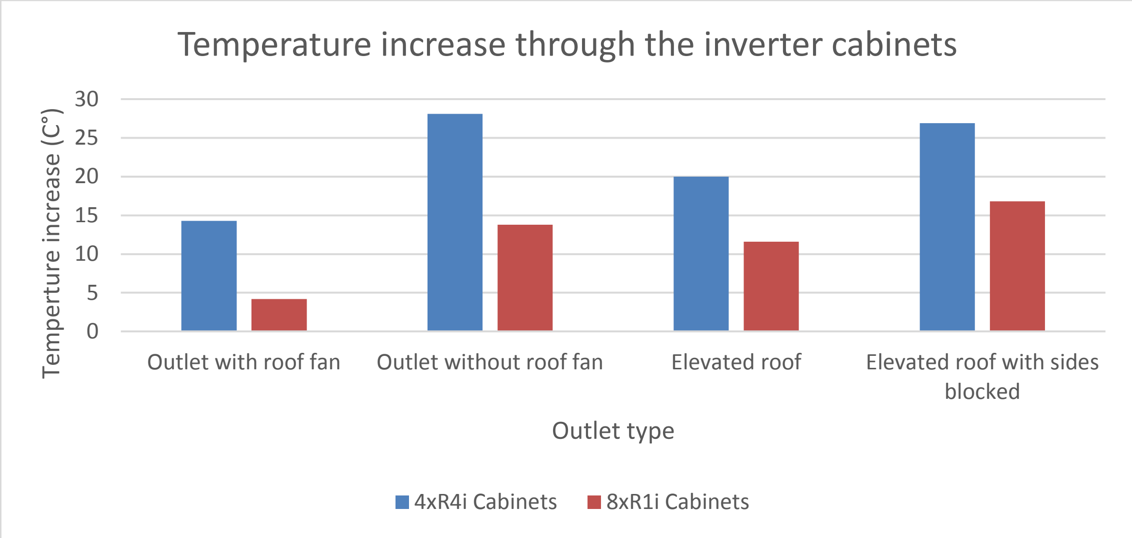


Figure 48, Temperature increase through the inverter cabinets

By comparing figures 47 and 48, it becomes clear that the outlets which provided the most volume flow through the cabinet also provided the lowest temperatures, and therefore the best cooling characteristics. This is no surprise, since the higher the airflow allows more convective cooling to occur inside the drive enclosure.

The original outlet with a fan proved to be the most efficient and reliable solution to keep the cabinet cool. The elevated roof provided by Rittal confirmed to be more effective than the outlet without a fan from ABB, however if the Rittal roof is to be used, it requires all 4 sides of the cabinet top to be free for the air to exit. If 2 of the sides are blocked, the Rittal solution does not bring any advantage compared to the ABB outlet without the fan regarding the cooling. However, the elevated outlet is cheaper and has less height compared to the normal outlet, which would bring more value for the customers.

As the inverter modules should not be operated in an ambient temperature higher than 50 Celsius degrees, the simulations proved that four R4i inverter modules inside 600 mm wide Rittal cabinet are not safe to operate without a roof fan. The R1i module cabinet with eight inverter units, however, does work under allowed temperatures for the inverter modules without a roof fan both with the ABB and Rittal solutions.

For further investigation, the R2i and R3i could be simulated to find out if they also operate under the 50 °C limit inside a cabinet without a roof fan. If these results turn out to be promising, then heat run tests could be done for final verification insuring that the R1i, R2i and R3i inverters are allowed to be used in a cabinet without a roof fan. Another possibility would be to simulate a situation where a cabinet without a roof fan is filled only with half of the inverter modules, which would enable installing all of the inverters near the cabinet inlet. When looking at all of the simulation results in chapter 7.2, the modules installed in the lower level received relatively cool air, in some cases there was not even a difference in the air temperature entering the modules whether a roof fan was used or not. However, a problem with filling the cabinets with only half of the modules is that in many cases it would take less money and space to combine the cabinet with a roof fan, than having wider cabinet than usual just to get a cheaper outlet.

A common problem with the air-cooled cubicles is that the hot air which is meant to exit the cabinet often starts to circulate inside the enclosure. This problem does not occur when using the outlet with a fan, but in other cases some circulation can be seen. The first problem spot is at the back of the cabinet where the hot air from the inverter modules exits. In this area, the air from lower modules raises up until it mixes with the flow coming from the upper modules. At this point, some of the air starts to circulate instead of exiting the cabinet. The second problem spot, which is common to the all of the cabinets without an outlet fan, is the front section where the suction created by the upper module fans draws air also from the top of the cabinet. This creates a loop where the module heats up air, and some of this heated air comes back to the module, which is opposite to ideal for cooling purposes.

To solve the air circulation problems inside the cabinets without an outlet fan, an air blocker could be applied at the upper module inlet level. This would block the circulation through the inverter modules, while ensuring that only fresh air from the inlet will enter the inverters. Even though the air blocker would probably be cheap to produce and easy to install, it would still add a new component to the cabinet, which could lead to customers preferring the simpler roof fan outlet option. If the cabinet design is changed, it is important to make sure that components such as inverter fuses and the switch will not overheat.

The elevated roof outlet worked quite well when all the sides were open. When the sides were blocked, the volume flow through the cabinet drastically decreased, making the air circulate inside the cabinets and allowing temperatures to go higher. A possible solution to this problem would be to raise the elevated roof higher, creating more area for the air to exit the cabinet. Further simulations could be done to find how much exactly the area of the exit holes affects the volume flow through the cabinet and what would be the optimal area size for the outlet exits. This information could help to create better outlets, and possibly enable using a cabinet without a roof fan.

9 Summary

The purpose of this thesis was to compare 3 different outlet types for ABB ACS880-104 inverters in Rittal-cabinets. The comparison was done by thermal simulations using FloEFD simulation software. First goal of the simulations was to find out if the inverter modules from frame sizes R1i to R4i can be used without a roof fan in the cabinet. Second goal was to find out if an elevated roof outlet would work better than the normal outlet from ABB without a roof fan. An additional goal was to measure and record pressure drop and air volume flow data from the R1i-R4i modules. This data was used to create simplified simulation models, and to delimit the range of simulated inverter modules by defining the inverter modules which would most likely have issues with overheating.

All the inverter modules were tested inside a wind tunnel to find out the pressure drop and airflow values for each inverter unit. The test results proved that the R4i and R1i modules should be the weakest links when also considering the heat losses each inverter module produces, so these two modules were chosen for simulating the effectiveness of the different outlets.

Simplified simulation models were created of the R1i and R4i inverter modules, by inputting pressure drop and heat loss data straight into the simulation software instead of calculating it during every simulation. The pressure drop data was taken from the test results, and heat loss information from the product manual. Also other components of the simulation model were simplified by removing parts and features such as screws, holes and chamfers, which would increase the calculation time of the simulation significantly, but would not change the results considerably.

According to the simulation temperatures inside the cabinet, the R4i modules produced too much heat to be used without the roof fan outlet. Without a roof fan in the cabinet, the air would start to circulate which causes the cabinet temperatures to raise too high for the inverter modules to operate reliably. The air circulation problems were common to both R1i and R4i modules, even though the R1i inverter cabinets managed to operate in a slightly lower temperature compared to the R4i module cabinets.

The elevated roof outlet provided by Rittal proved to be more effective in comparison to the ABB outlet version without a fan. This outlet had air holes to all 4 directions of the cabinet walls, which created more volume flow through the cabinet. However, often the customers using a Rittal cabinet would install the enclosure into a row of cabinets, blocking the side outlets. Because of this, the elevated roof outlet was also simulated with the sides closed, which lead to similar results with the normal ABB outlet without a fan.

In the end, the results proved that the most secure and effective solution for an air outlet is the outlet with a fan. The elevated roof outlet could be possibly used in the future, but for this the circulation of air should be eliminated. The circulation could be stopped or reduced by for example installing air blockers inside the cabinet. The elevated outlet could bring benefits, as it has low height and could therefore lower the total height of the inverter cabinet.

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